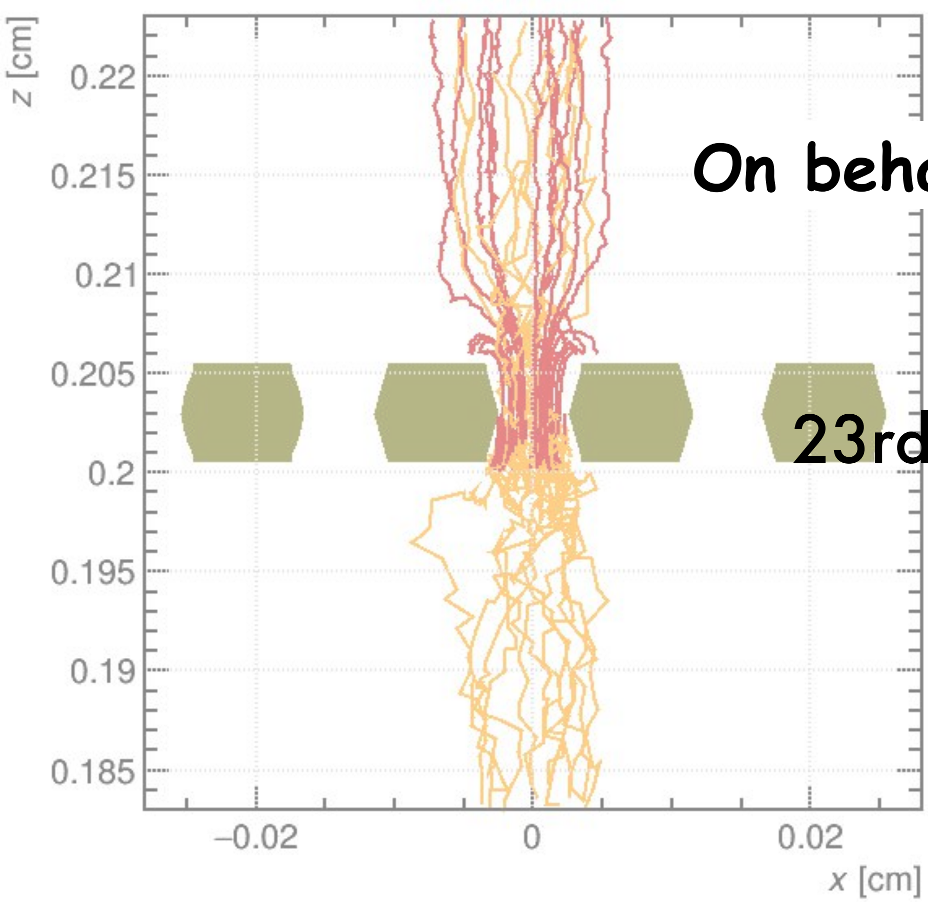
Simulation studies of multi-layer GEM detectors



Licheng Zhang
On behalf of CMS group of Peking University

23rd-27th Nov 2022 CLHCP (Nan Jing)

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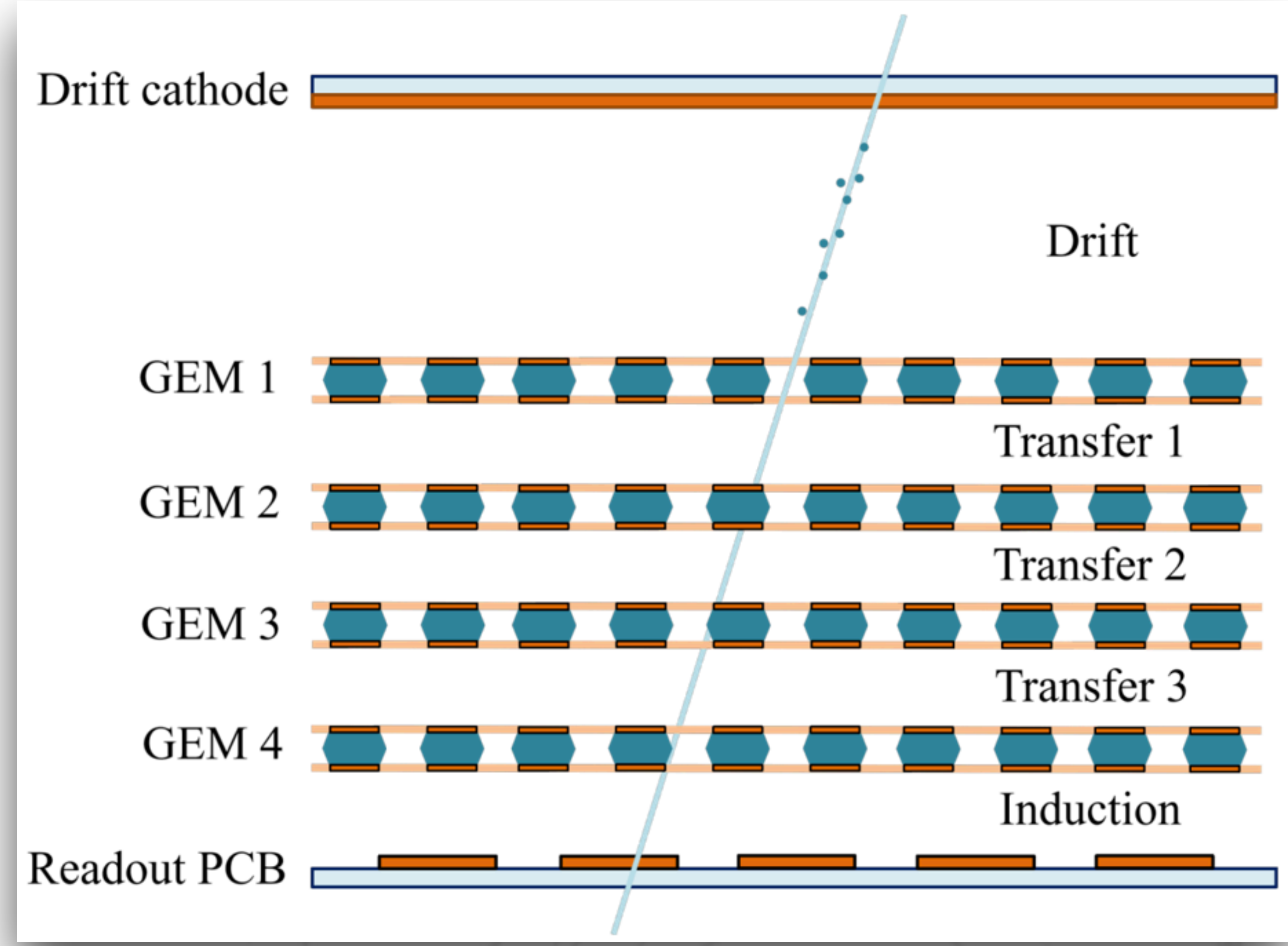
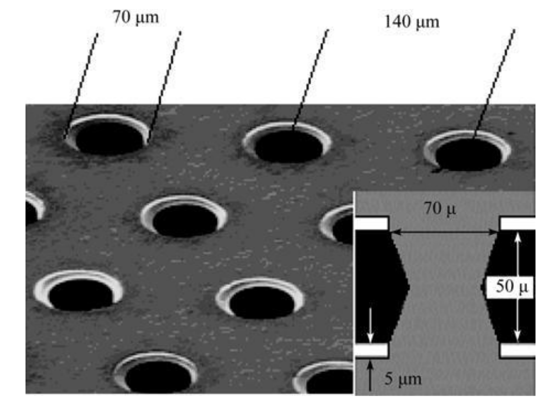
- **Motivation & Introduction**
- **Approches**
- **Results**
- **Summary & Outlook**



Introduction & Motivation

Traditional gaseous detector → micro pattern gaseous detector(MPGD)

- High counting rate in strong radiation environment at high energy collider.
- Works in strong magnet-electric fields.
- Provide better performance.

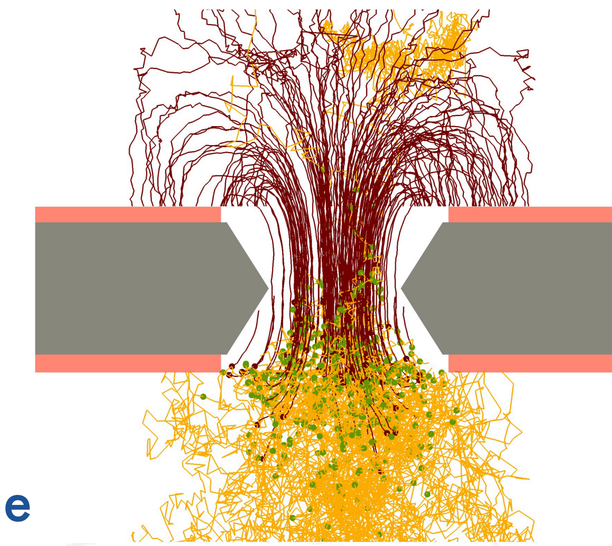


Gaseous Electron Multiplier (GEM)

- Stable/lower discharge damage/less aging problems/cheaper

Multi-Layer GEM detectors

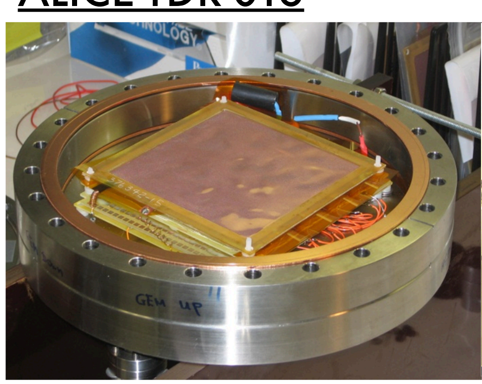
- Greater gain with lower voltage working point
  - Lower operating voltage
  - Lower discharge probability
  - Lower Ion Back Flow(IBF)

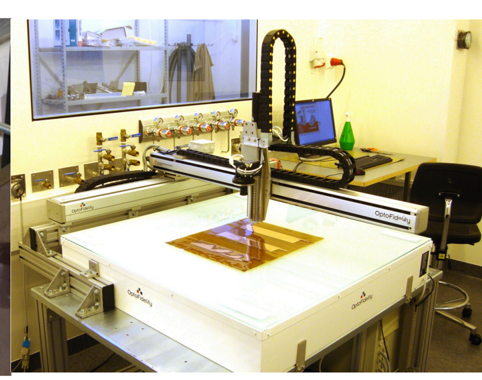


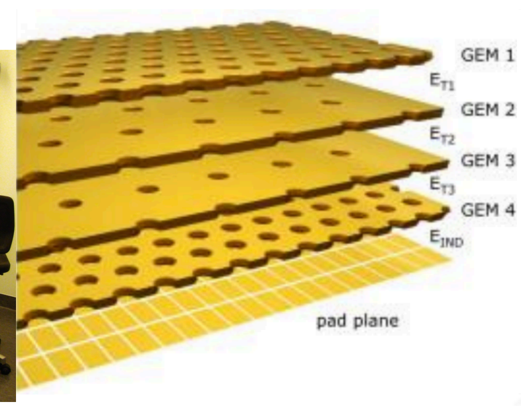
Triple-GEM tech. are widely used while Quadruple-GEM are not

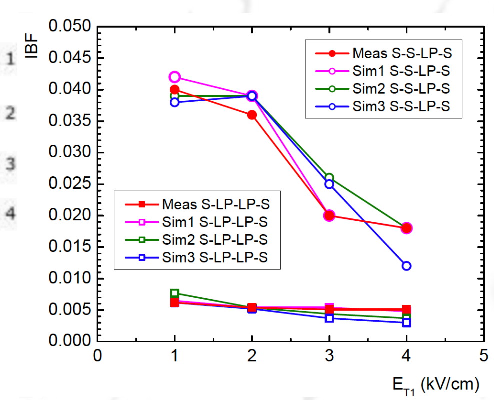
- Example: ALICE TPC(Time Projection Chamber) Upgrade
  - Lower IBF(Ion back flow) ; Tolerable field distortion.
  - Better position & energy resolution...

ALICE-TDR-016









Which are also meaningful upgrade concepts for the other experiments and detectors

It is meaningful to study structure design, mechanism and performance of Multi-Layer GEM !

★ Find stable and reliable Work Flows to simulate Multi-Layer GEM based detectors.

★ Study performance of Multi-Layer GEM detectors and understand its mechanism.

★ Optimize structure/geometry to get better performance, i.e. to ameliorate high discharge probability/low counting rate situations.

★ Provide reference for Multi-Layer GEM based detector experiments.

Approaches work flow

Particle by particle Traditional Full Simulation

Detector Modeling
Ansys: geometry; Materials; Electric Field; Weighted Field;

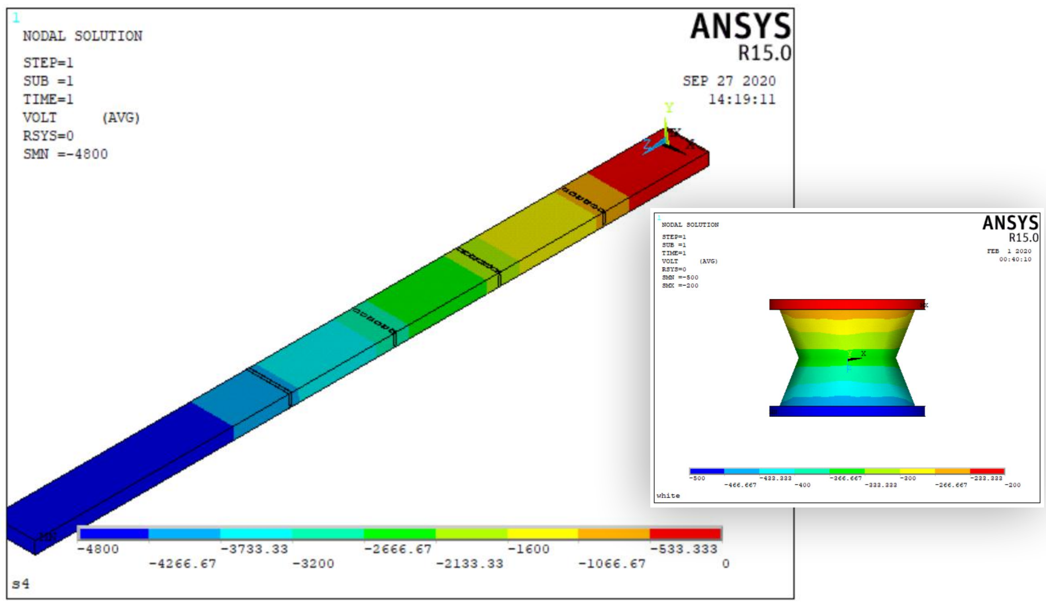
Garfield++ Initialization
Magboltz: Gas properties;
Heed: Particle properties;
Garfield: Sensor range, time windows, etc.

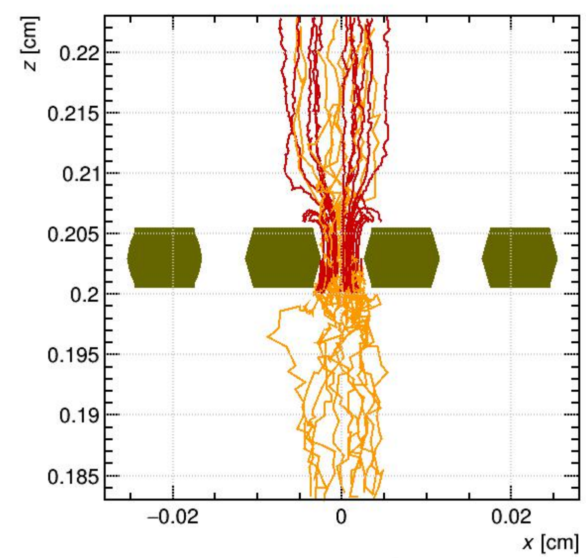
Primary Ionization
Heed: Details of primary ionization and other processes based on the properties of insert particles.

Charge Transportation
Garfield: Details of charged particles transport, avalanche in the gas mediums.

Signal Readout
Ansys: Weighted fields;
Garfield: Charge induction; signal convolutional;

Data Analysis
ROOT: Data Processing; Plotting;





Step by step (Parametric) Simulation

Primary Ionization
Parameterization for primary electrons:
Position; Energy;

Electron Transportation
Parameterization for electron transportation:
Shift; Spread;

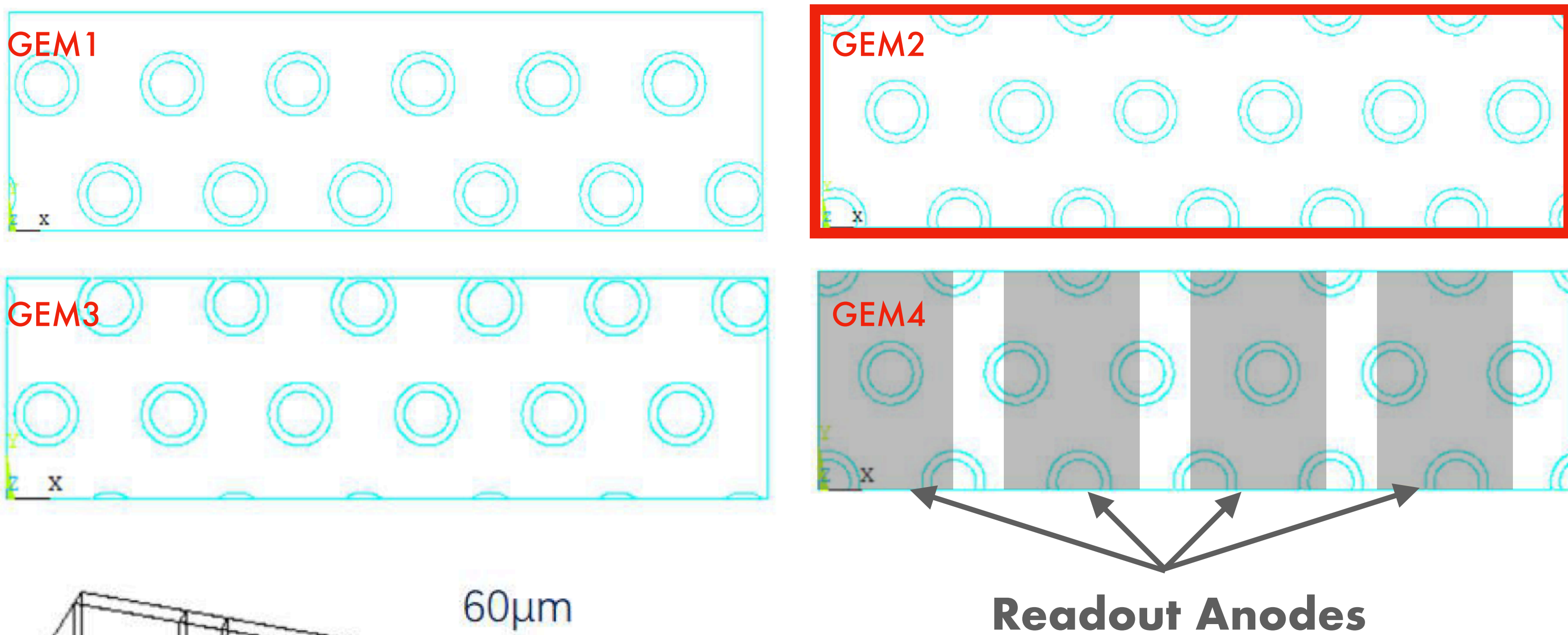
Gain
Parameterization for gain on each GEM foil:
Avalanche; Transparency;

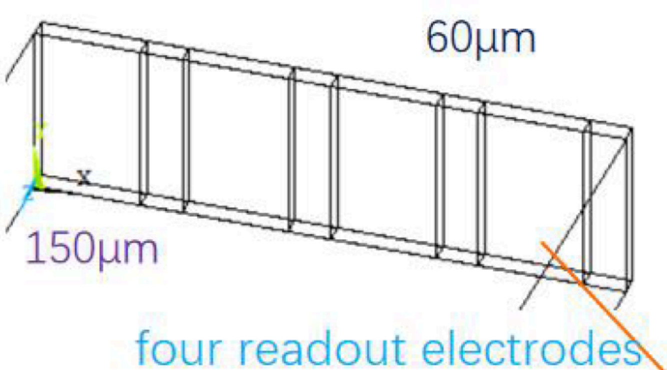
Signal Induction
Fast signal induction:
Charge collection; Convolution;

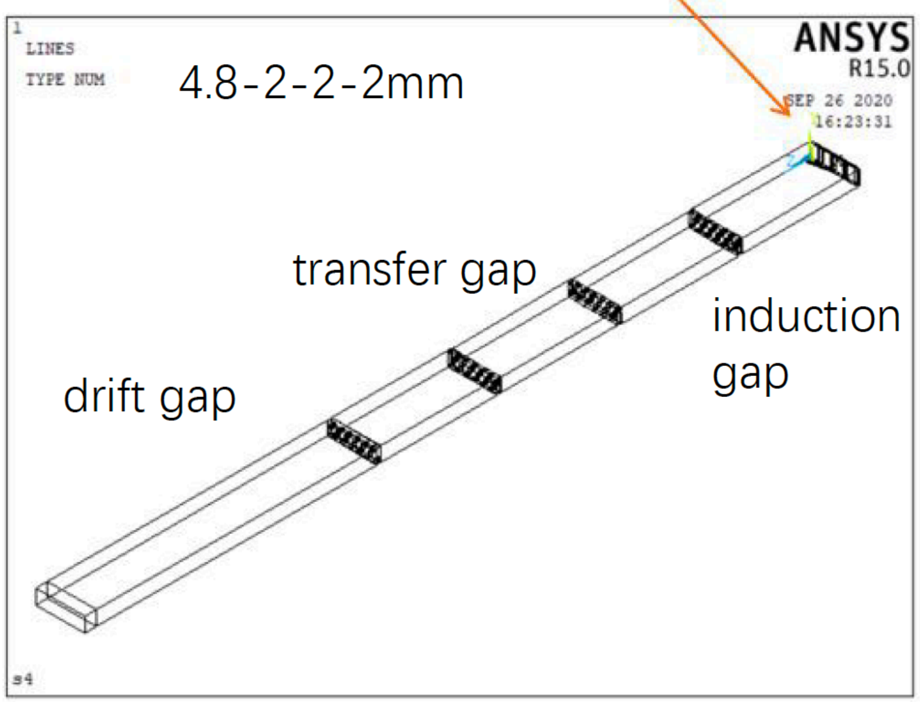
Tuning
Optimize parameters:
Comparison between simulation and experiments with several parameters.

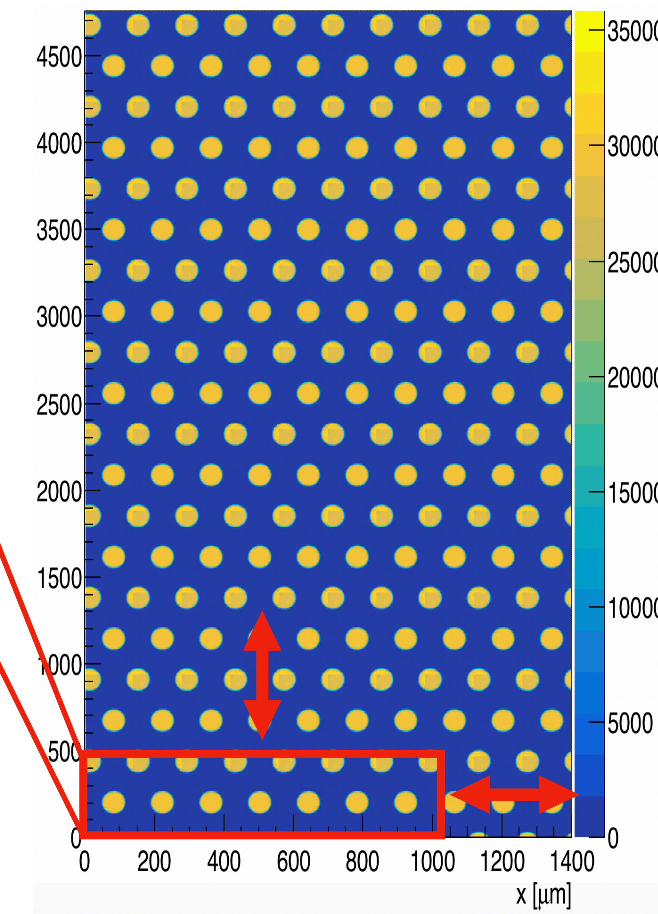
Re-Modeling
Optimize parameters:
Use new parameters to do the simulation step by step.

Approaches geometry & condition

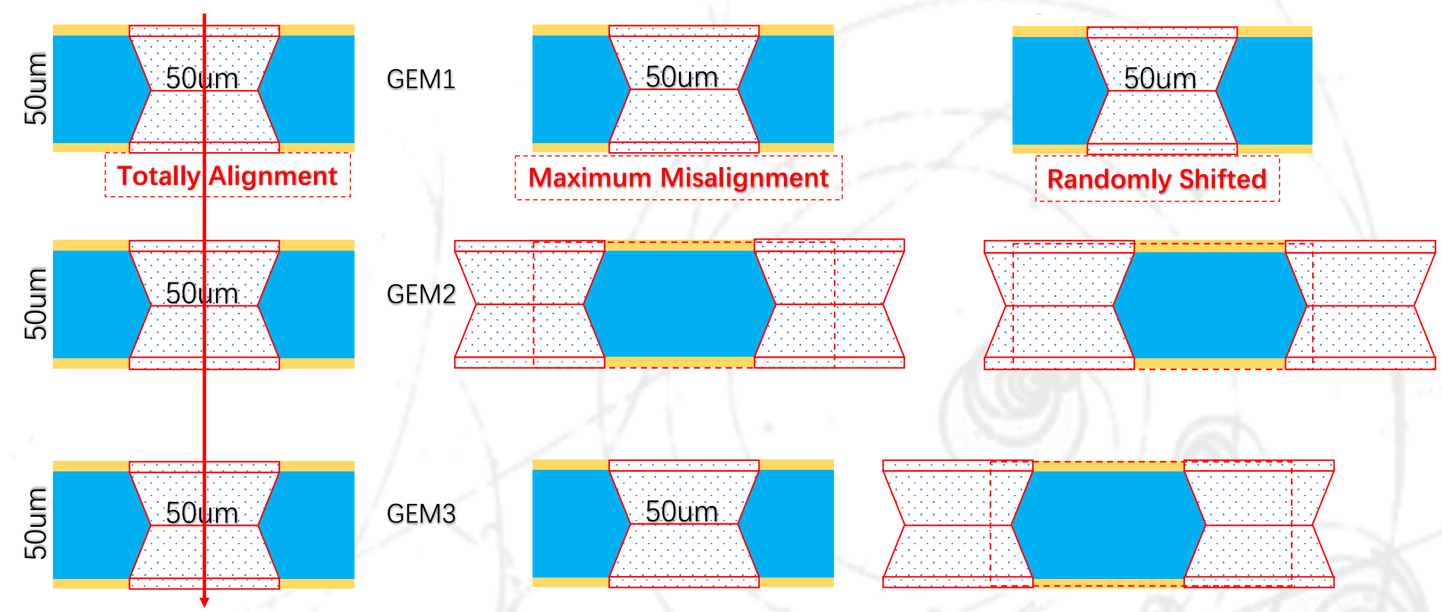




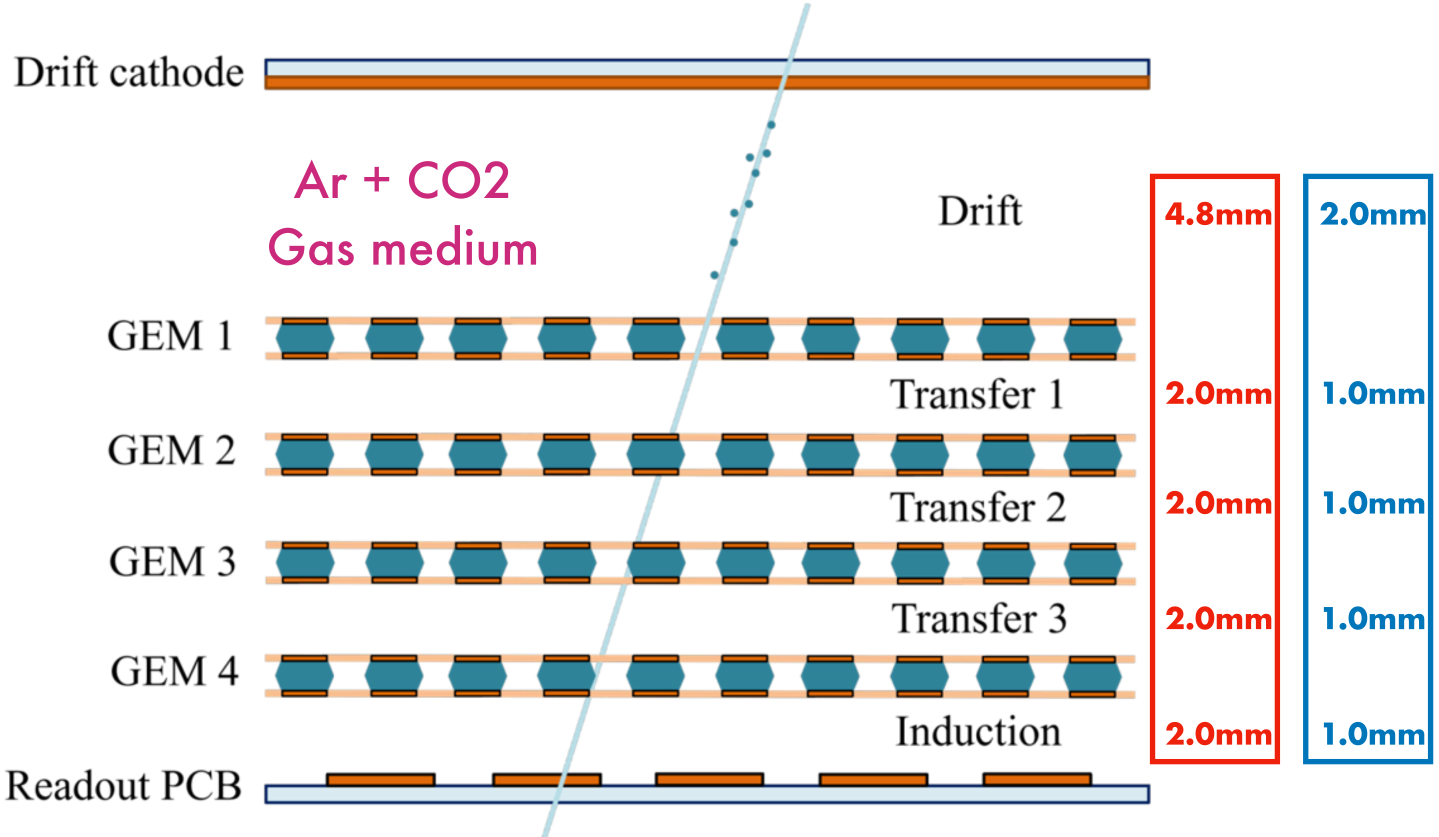




Periodically expand in x, y directions.



Partial (randomly) misalignment the micro hole.



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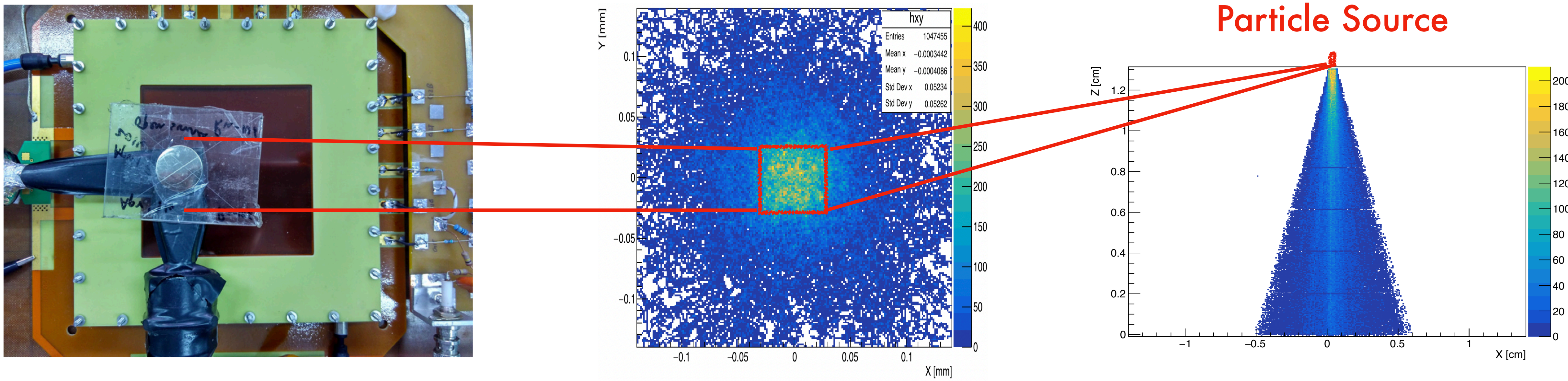
★CMS Quadruple-GEM

- ★ Same total thickness as CMS new Triple GEM detector.
- ★ Fit the CMS Muon detector envelope.
- ★ Compare with the Triple-GEM detector.

ALICE

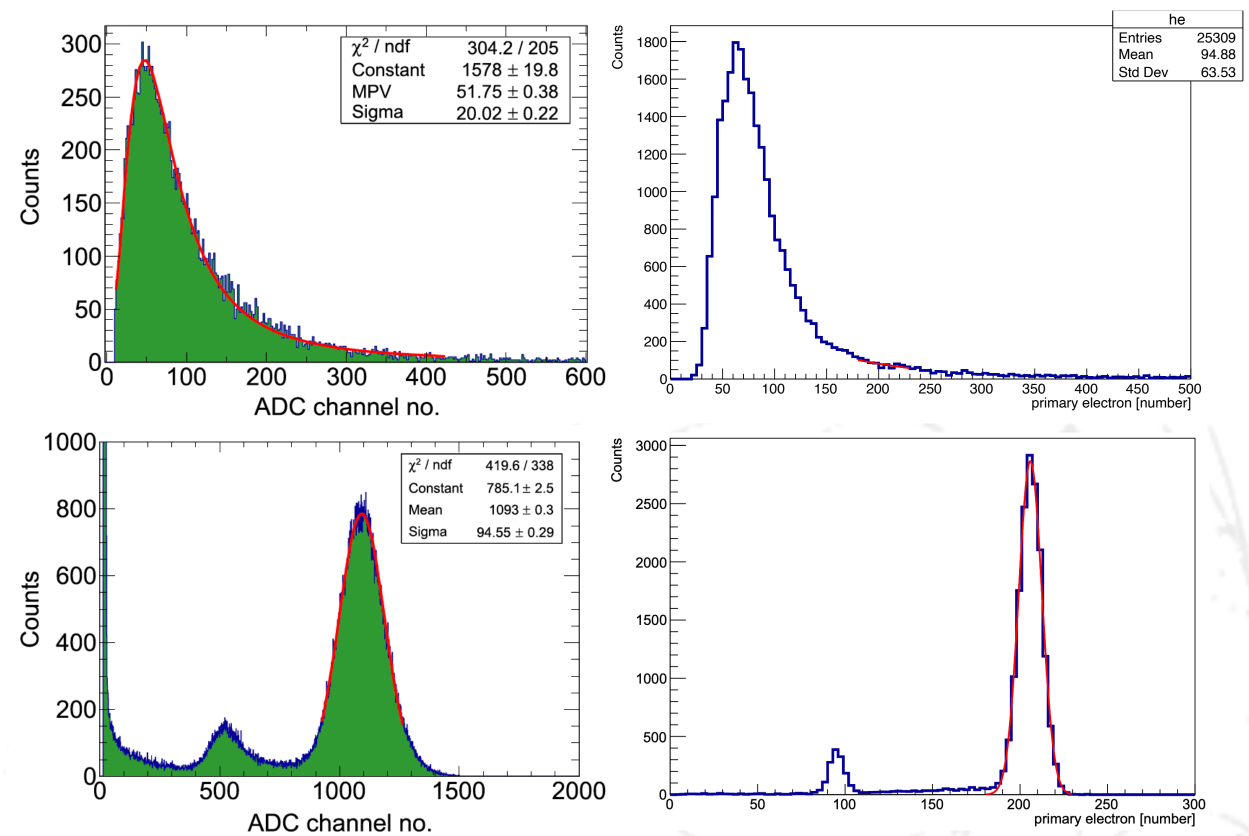
- ★Same as the ALICE new TPC structure.
- ★Able to compare with abundant experiment data.

Particle Source



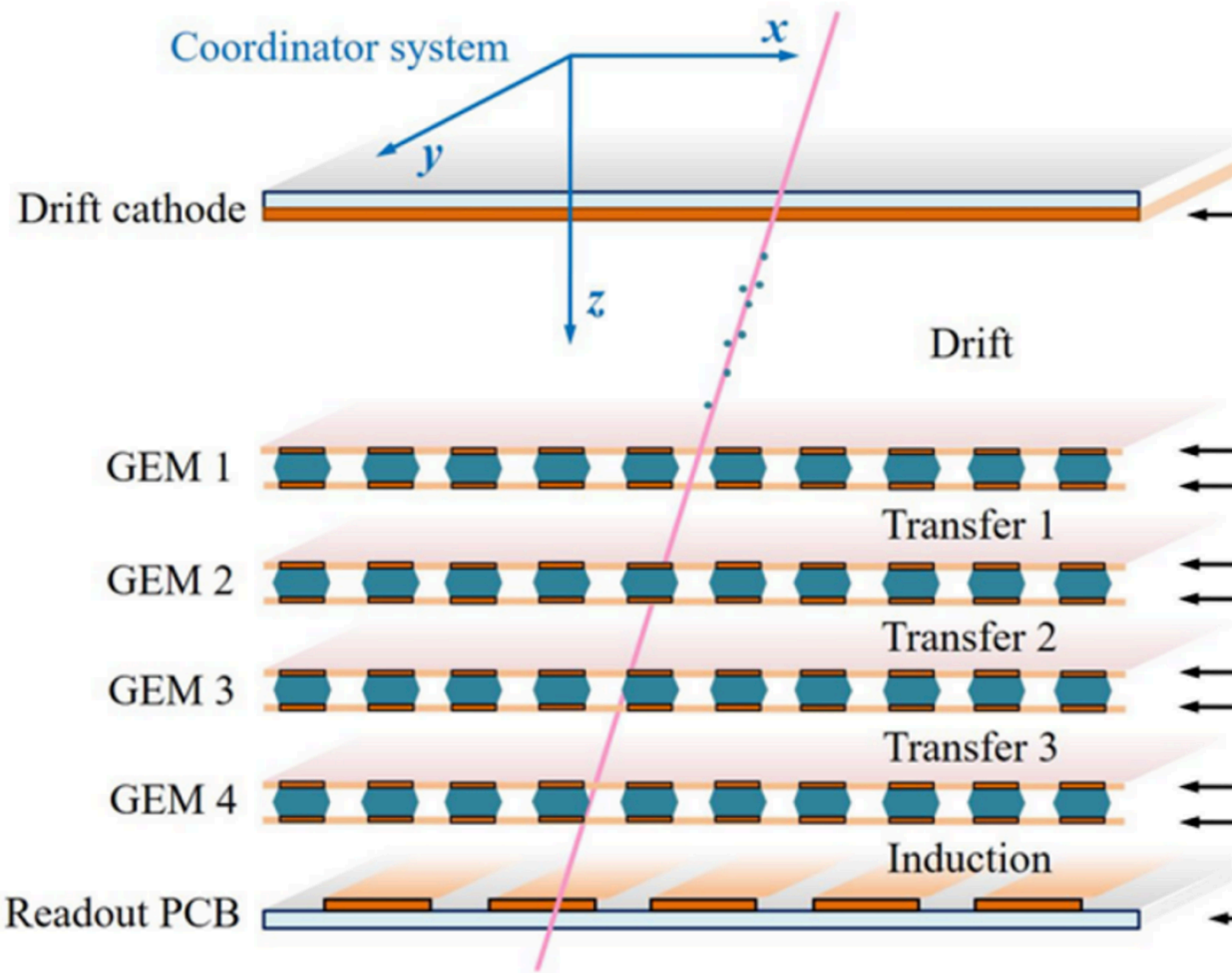
- 150 GeV muon

Particle Source
- Fe-55 X-Ray (5.89keV)
- Ru-106-Rh beta (E_{max}=3.54MeV)

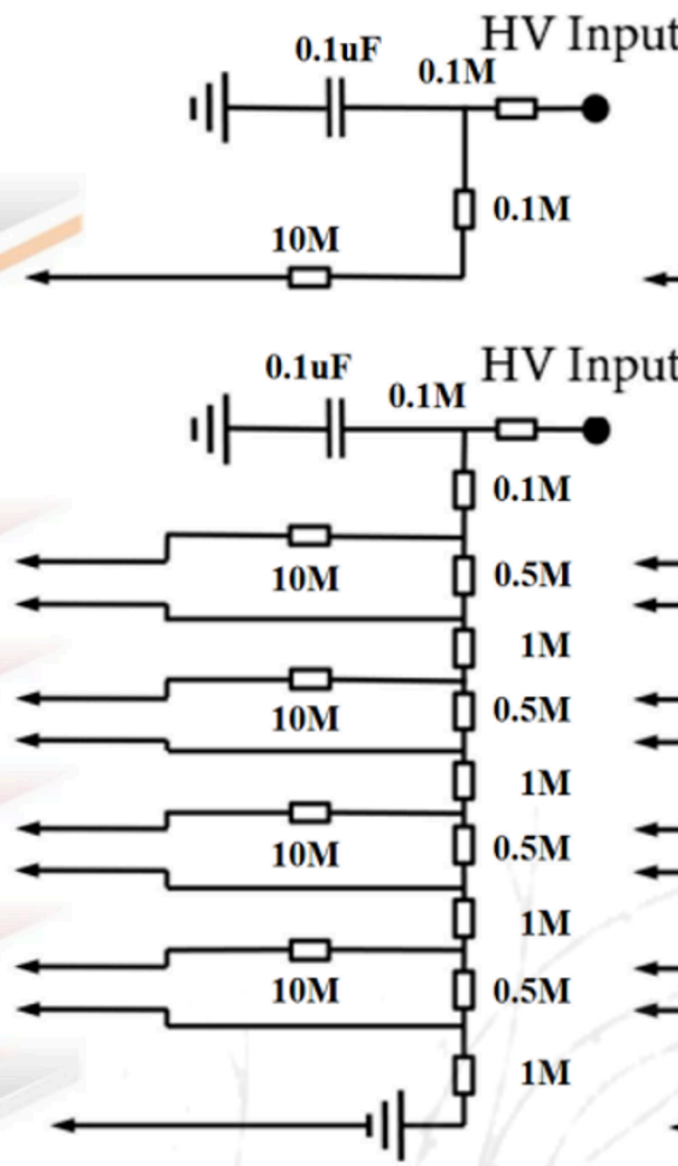


Experiments Simulation

* Particle Source are generated by self-defined generators or Heed



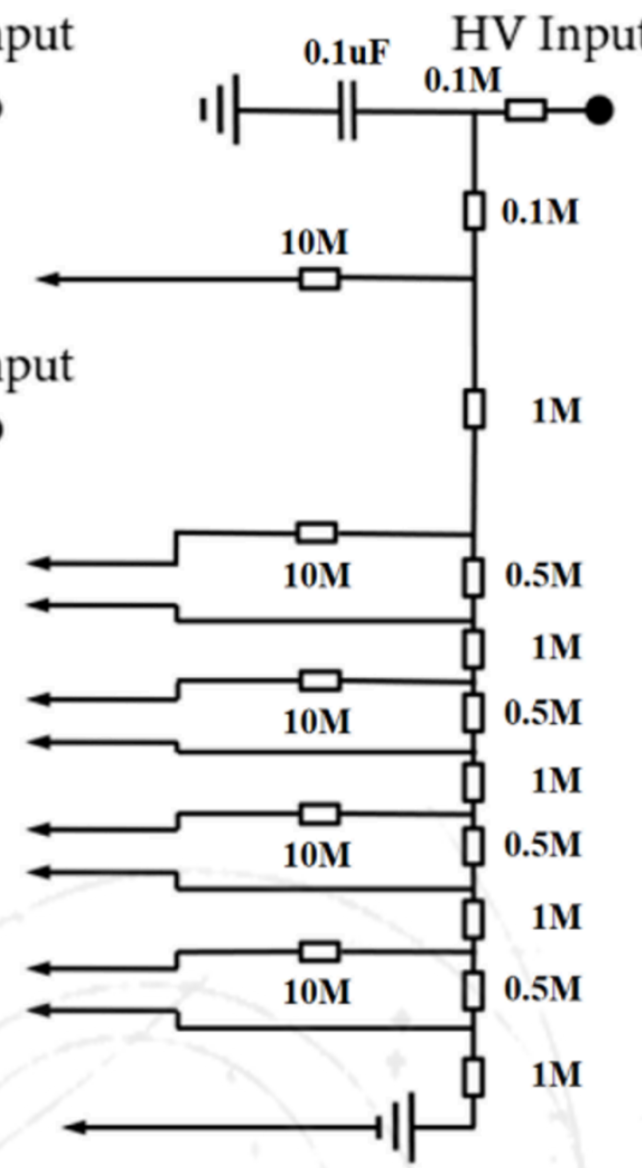
Double High Voltage source



HV divider for independent drift field configuration

Double HV

Single High Voltage source



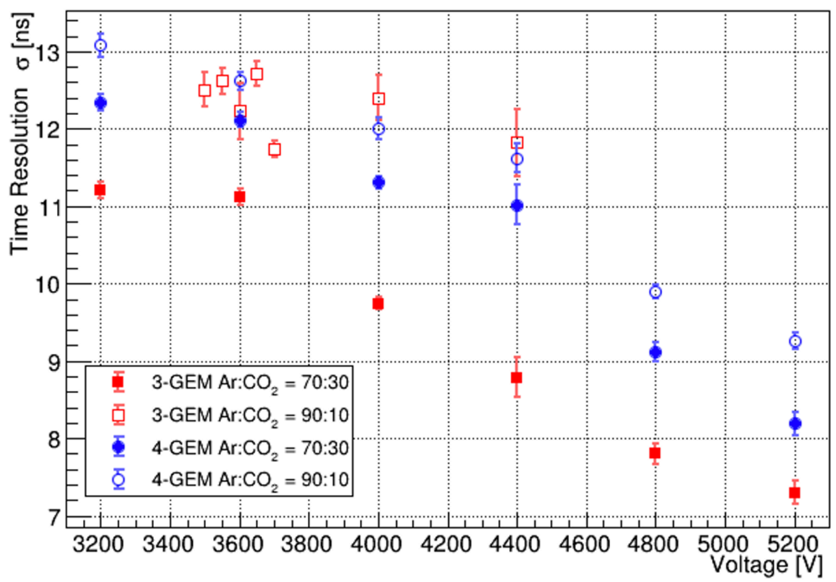
conventional HV divider

Single HV

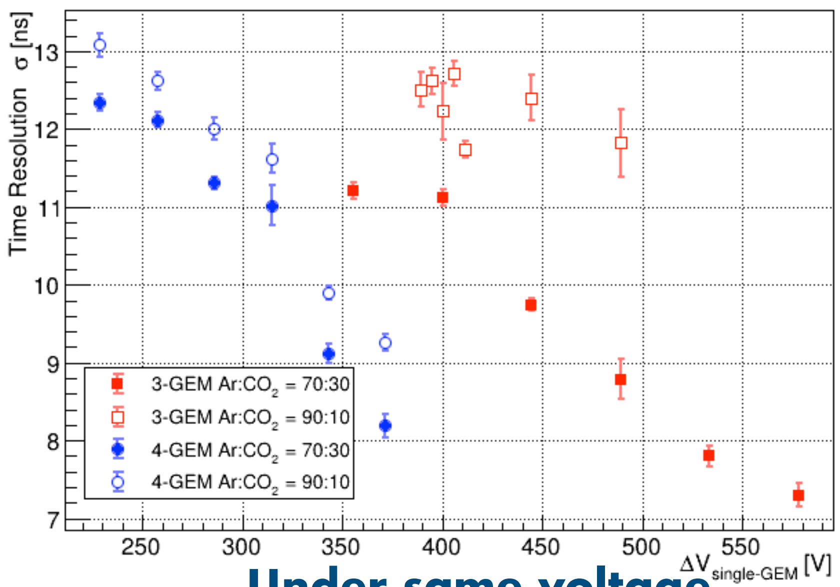
In order to control the electric field strength of the drift volume only.

Results time resolution

Comparison of Quadruple GEM : Triple GEM (Single HV)



Total voltage applied on GEM

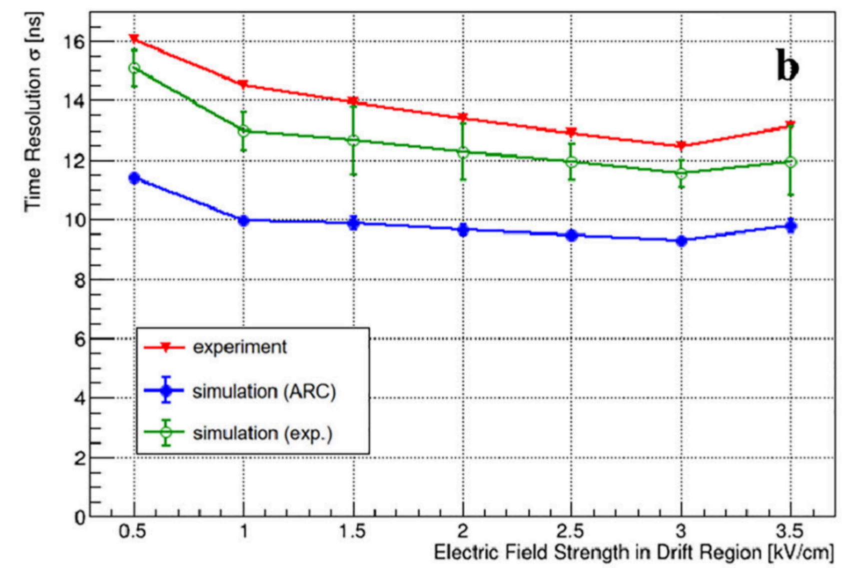


Under same voltage applied on single GEM foil

- Time resolution is slightly worse than triple-GEM (CMS GEM).
- Reason: used ALICE 4-GEM structure with longer drift distance and larger total thickness.

- Could be improved with the optimization of GEM structure.
- 4-GEM can achieve same time resolution at lower voltage drop on single GEM foil.

Comparison of Simulation : Data (4-GEM, Double HV)



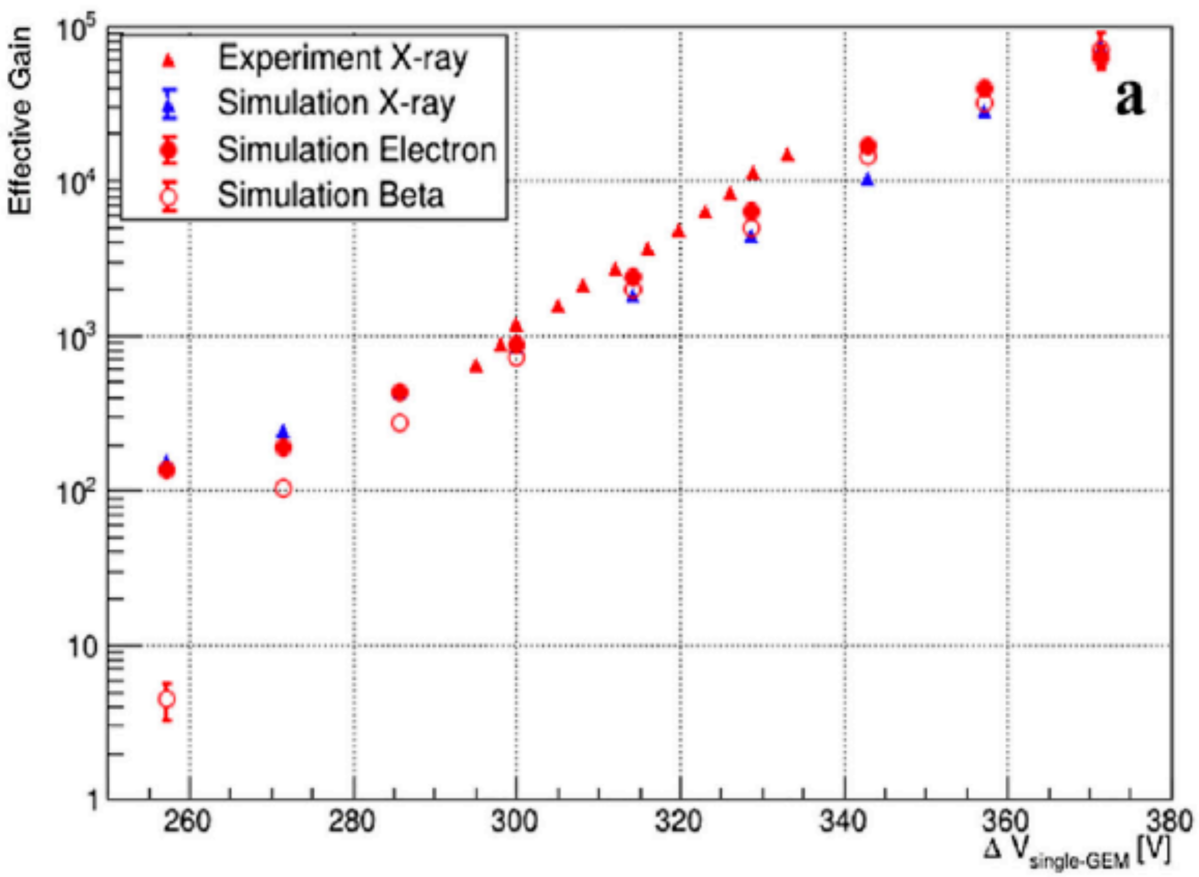
E-Field in drift region

- The simulation and experiment result have very similar tendency.

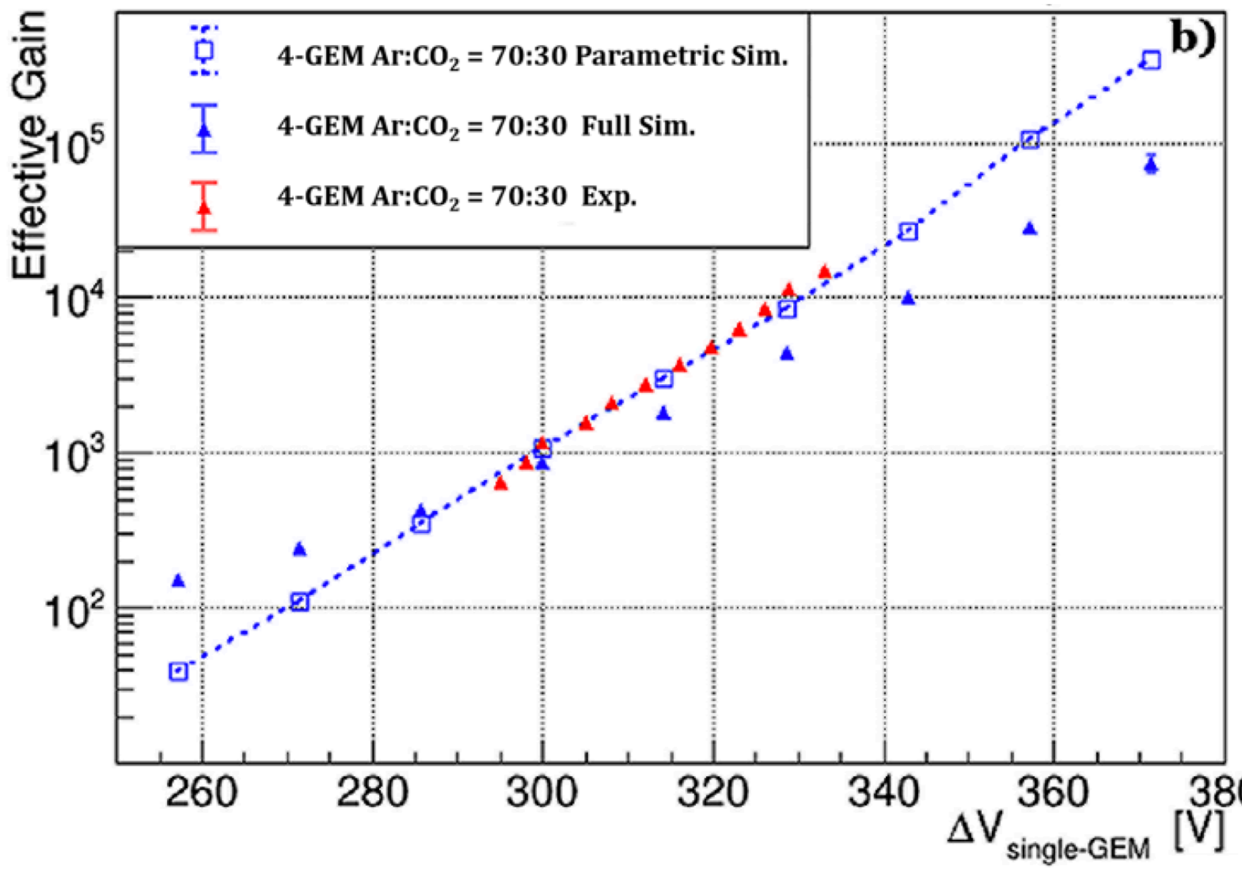
- ARC methods provide better time resolution.

- Noises can be estimated by comparing triple-GEM Sim. result with Exp. temperately (backup)

Effective Gain



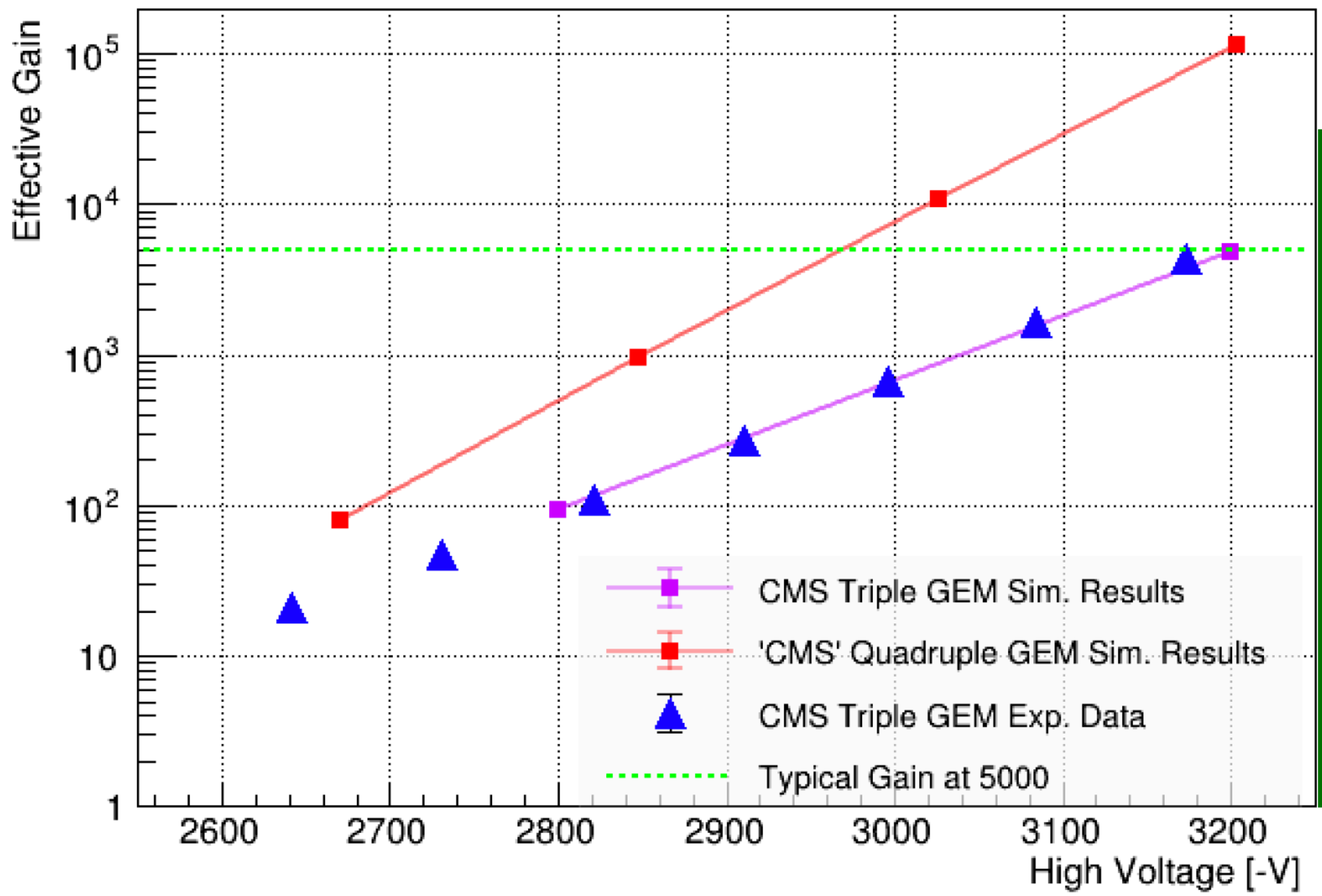
Effective gain for different source (Single HV)



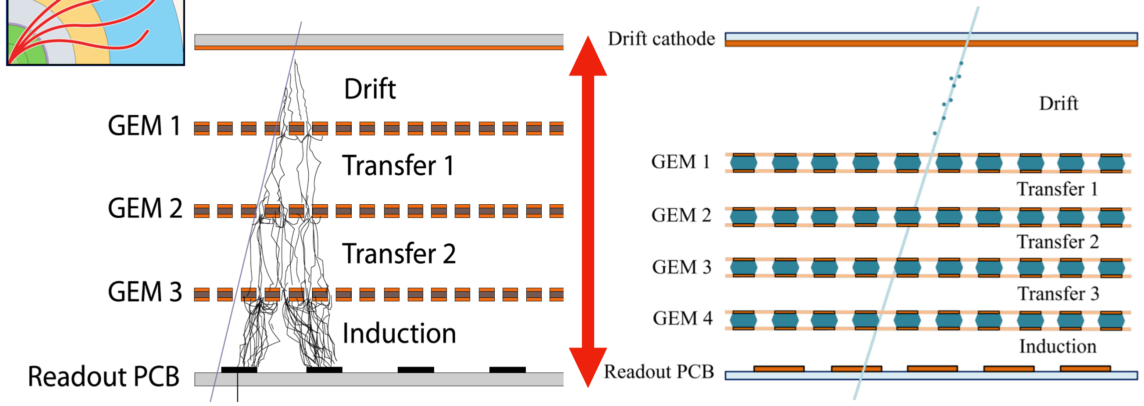
Comparison for Full Simulation, Parametric simulation and data(X-Ray)

- Effective gains with different incident particle are similar as expected.
- Simulation gain results smaller than experimental results (which is a well known phenomenon caused by many reasons.(Penning Factor, minimum free time, etc.) → we are also digging into.)
- Parametric simulation result have good agreement with experiment data.

Effective Gain



★CMS Quadruple-GEM



★ **Same total thickness as CMS new Triple GEM detector.**

★ **Fit the CMS Muon detector envelope.**

Comparison of CMS Triple-GEM, "CMS Quadruple-GEM" and Triple-GEM data (Parametric Simulation)

- Parametric simulation result have good agreement with experiment data.
- Quadruple-GEM can reach same gain at lower total voltage than Triple-GEM.
  ★ Could reduce the discharge rate with the same performance.

Summary & Outlook

- **Complete simulation process has been established.**
  - Full simulation as well as parametric simulation process.
- **Various performances characteristics studied:**
  - Time/spatial resolution;
  - Transparency; Efficiency;
  - Influence of different working conditions;
  - Comparison of simulation/experimental data, Quadruple/Triple GEM.
- **Understand the results theoretically or technically.**

- **Optimize the programs and toolkits.**
- **Understand mechanisms.**
- **Optimize the working condition:**
  - Gas medium; Electric-Magnetic fields;
  - Detector structure; readout design; etc.
- **Study about more performance:**
  - Ion back flow; Space charge effect; Discharge probability;
  - Maximum counting rate; PID; etc…

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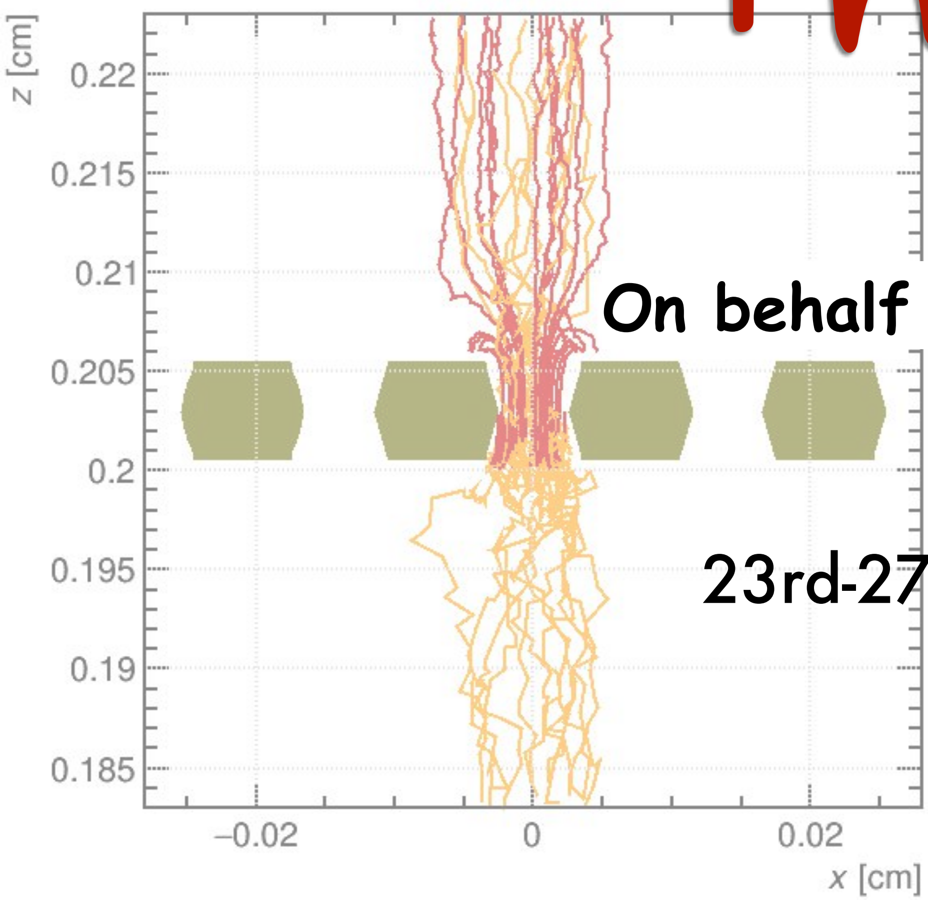
Simulation studies of multi-layer GEM detectors

Thank You!



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backup

Backup

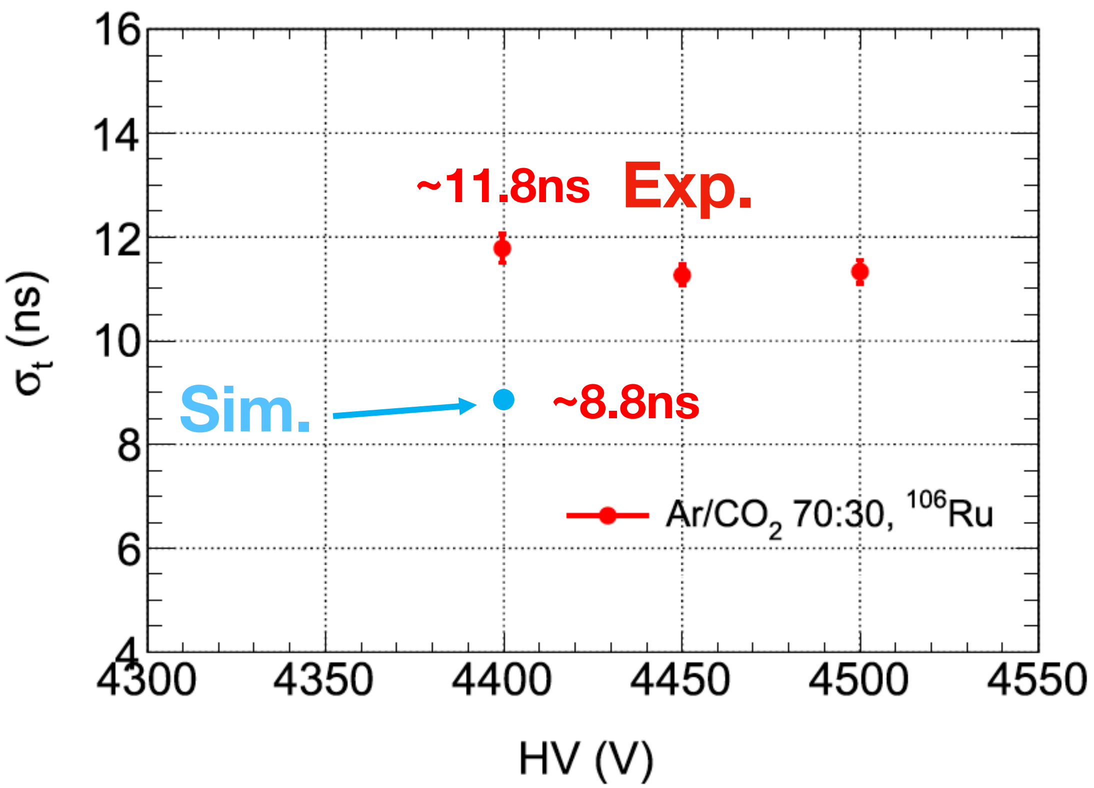
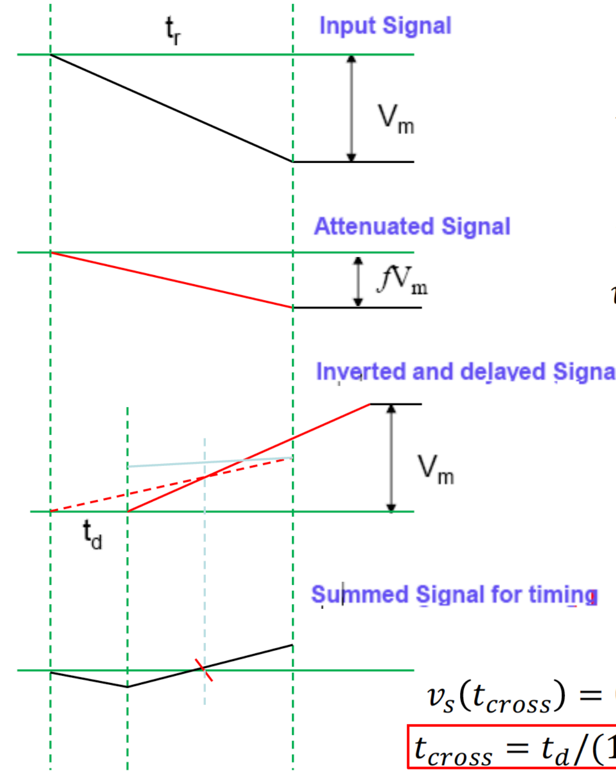


Fig. 8. (top) Time spectrum at 4450 V and (bottom) time resolution as a function of applied HV.

- Noises are estimated by comparing triple-GEM Sim. result with Exp. temperately.

ARC timing

For signals with different rise times



$$v_1(t) = \frac{v_{max}}{t_r} * t, \quad 0 < t < t_r$$
$$v_2(t) = v_{max}, \quad t > t_r$$

$$v_{f1}(t) = f\frac{v_{max}}{t_r} * t, \quad 0 < t < t_r$$
$$v_{f2}(t) = f v_{max}, \quad t > t_r$$

$$v_{d1}(t) = -\frac{v_{max}}{t_r} * (t - t_d), \quad t_d < t < t_r + t_d$$
$$v_{d2}(t) = -v_{max}, \quad t > t_r + t_d$$

$$v_s(t) = v_{f1}(t) + v_{d1}(t)$$
$$= f\frac{v_{max}}{t_r} * t_r - \frac{v_{max}}{t_r} * (t - t_d), \quad t_d < t < t_r$$

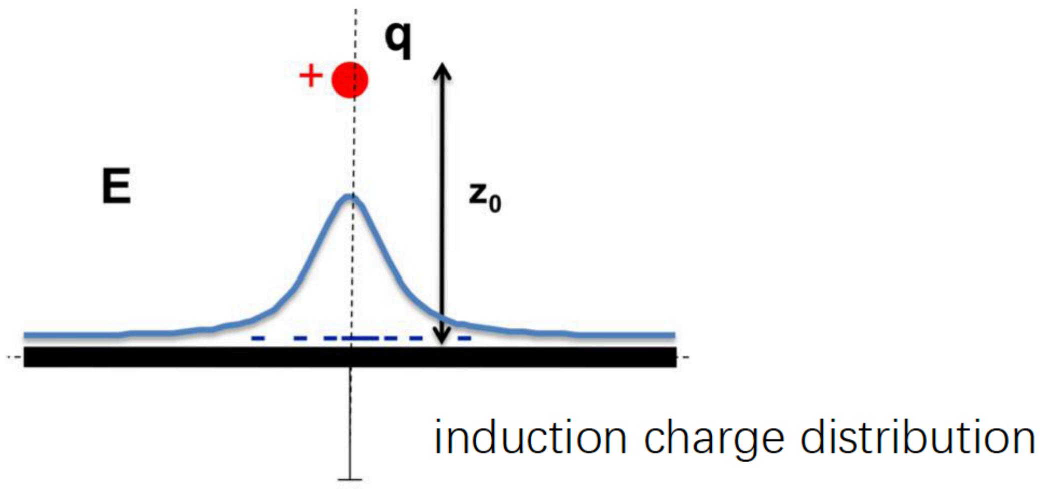
$$v_s(t_{cross}) = 0$$

$t_{cross} = t_d/(1-f)$, $\quad , t_{cross} < t_r \quad$ $t_d < t_r/(1-f)$

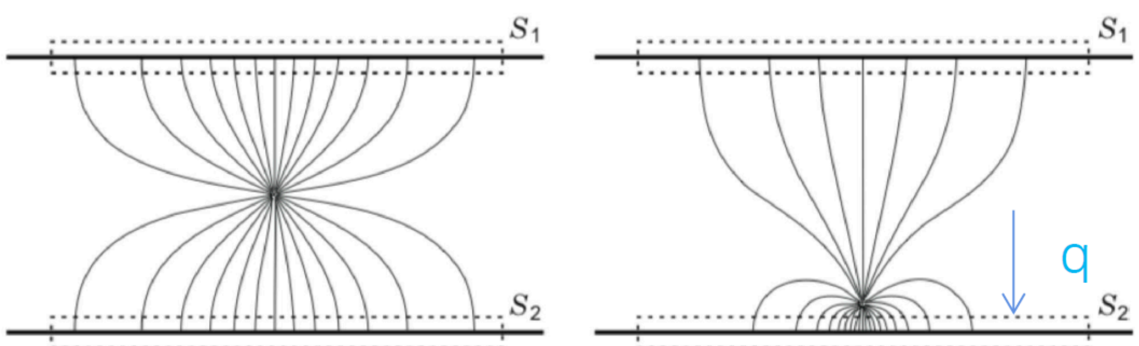
No rise time & amplitude dependence

the time of zero crossover occurs *before* the attenuated input signal has reached it's maximum pulse height.

calculation method of induction signal



current flow begins instantaneously when the charge begins to move.



the amount of charge induced by the readout electrode is increasing continuously.

1. solve the poisson equation at each step on the drift of the electron-ion pair(very complicated)
2. solution (Shockley-Ramo theorem):

$$i(t) = q \cdot \vec{E}_w \cdot \vec{v}$$

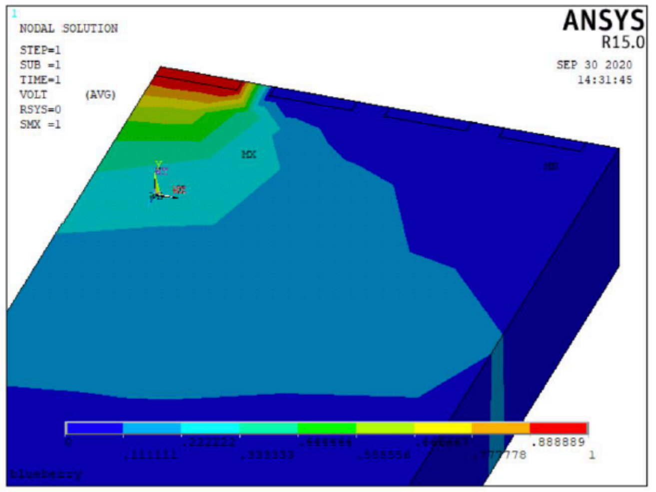
with q: charge; E_w: weighting field; v: velocity

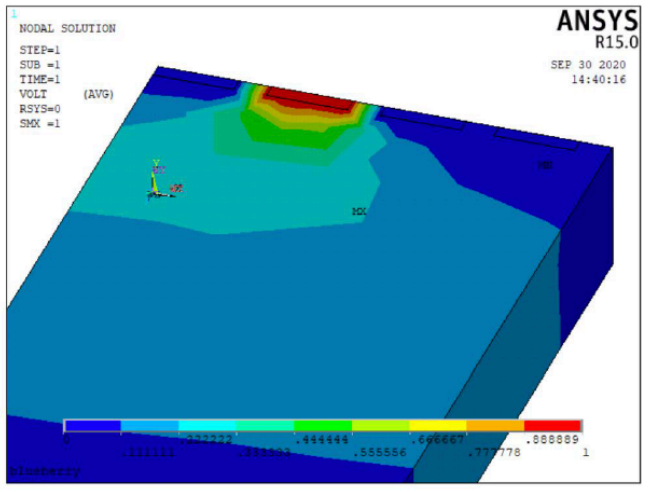
$$Q(t) = \int_0^t i(\tau) d\tau = q \int_{x1}^{x2} \vec{E}_w d\vec{x}$$

How to get the weighting field?

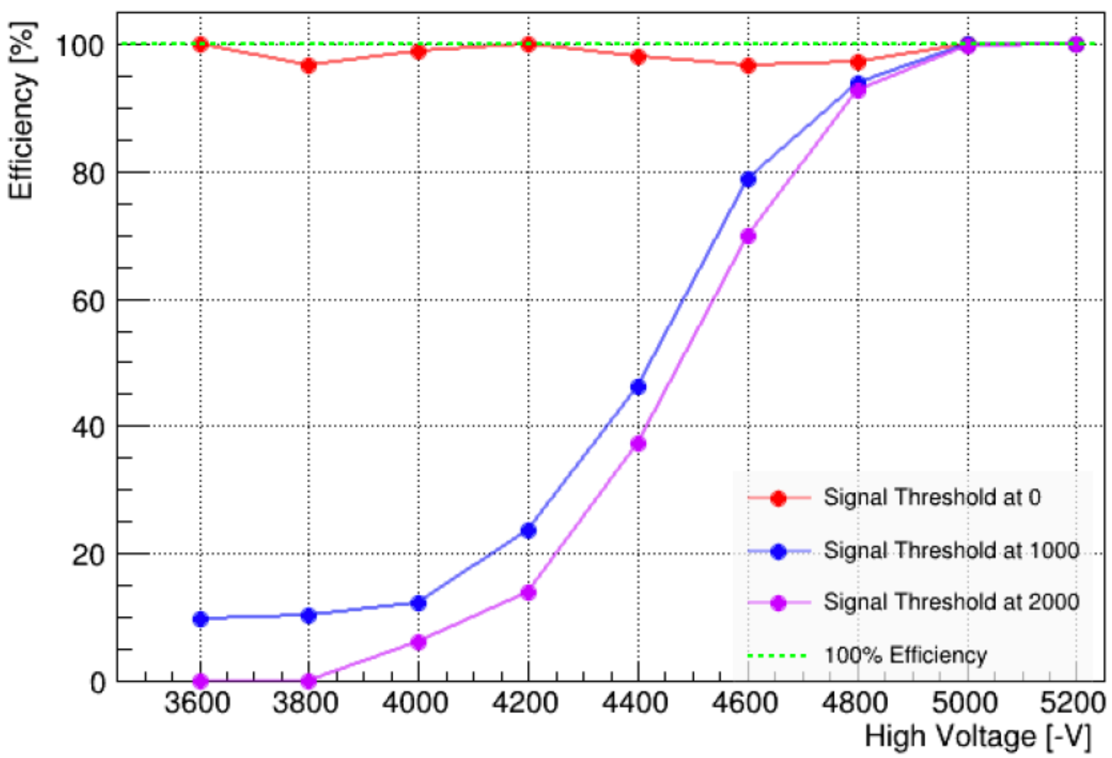
– calculate the electrostatic field for each electrode by:

- removing the signal charge
- setting the electrode to U = 1V and all others to 0 V

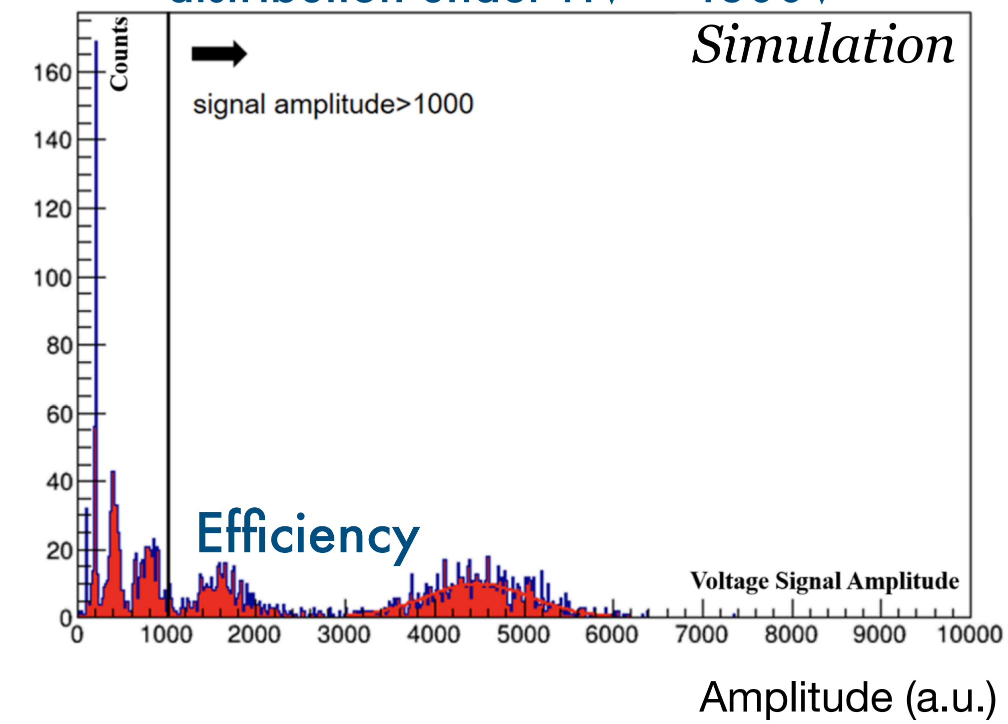


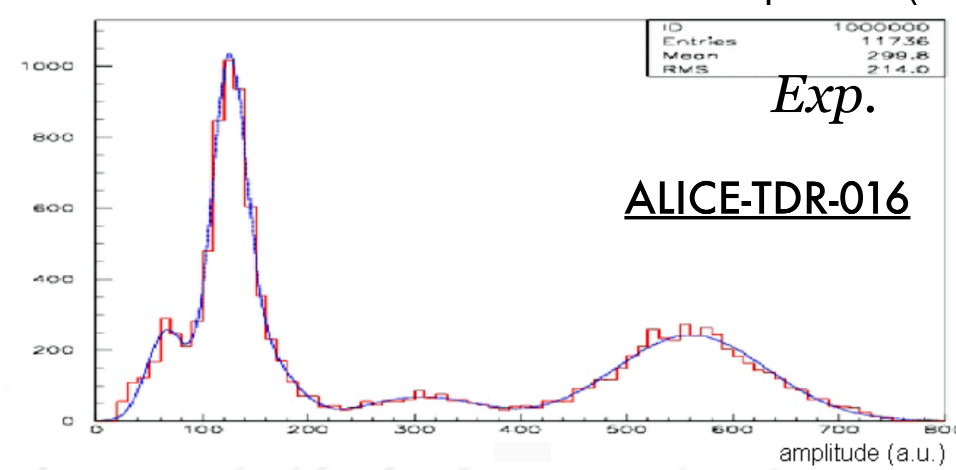


Backup



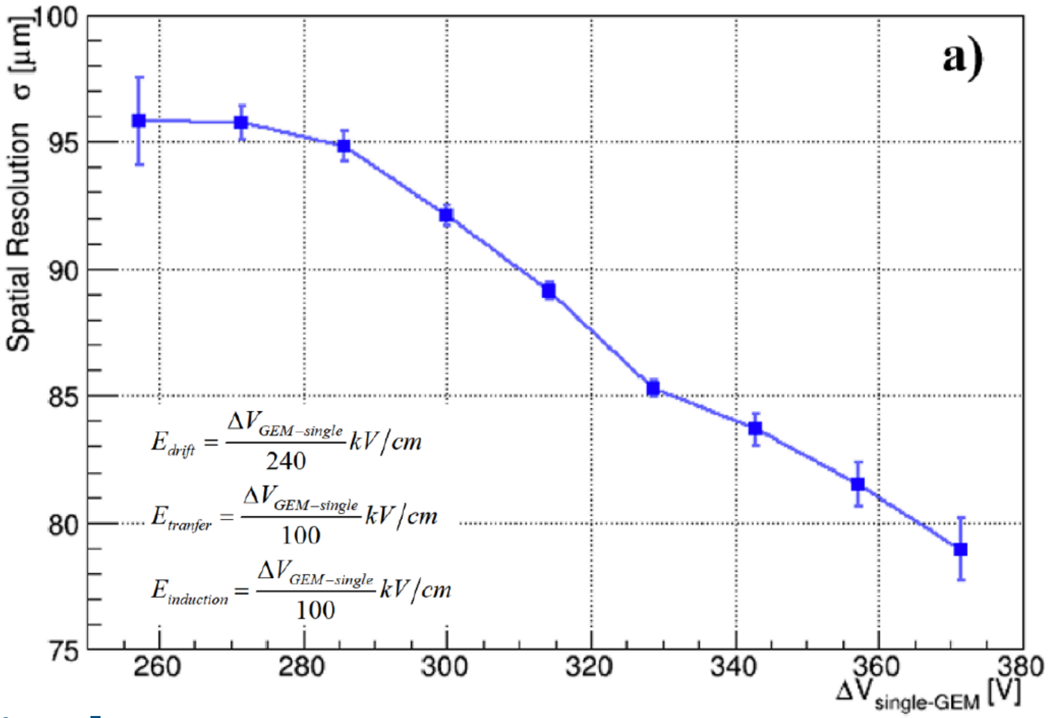
A typical result of signal amplitude distribution under HV = 4800V



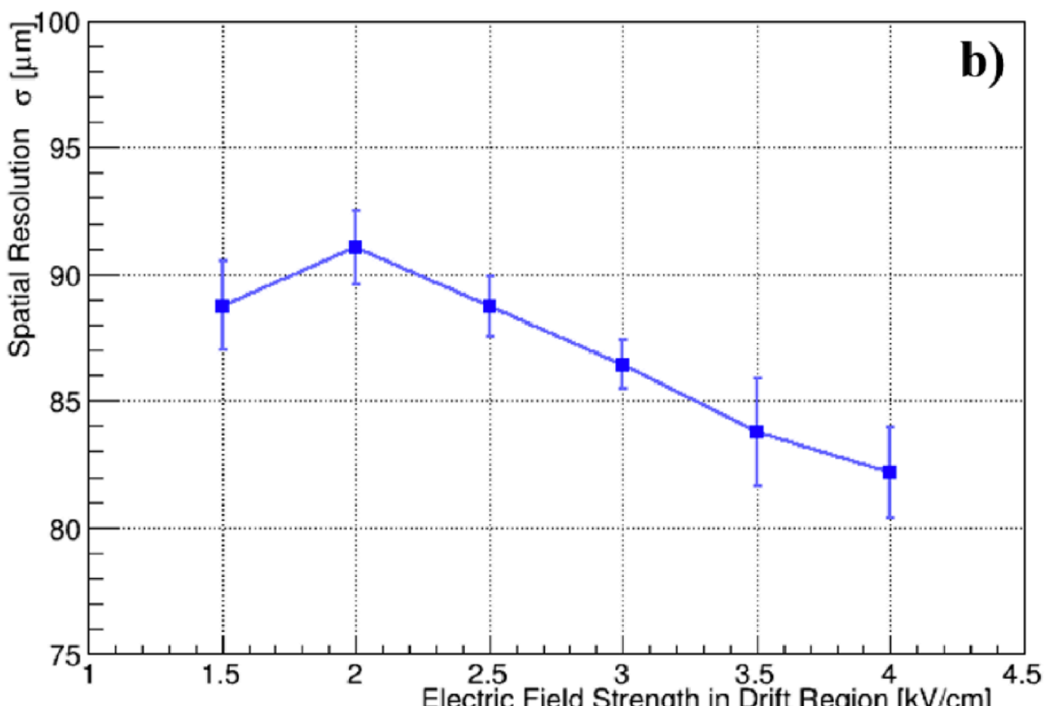


A typical result of signal amplitude distribution of one layer GEM.

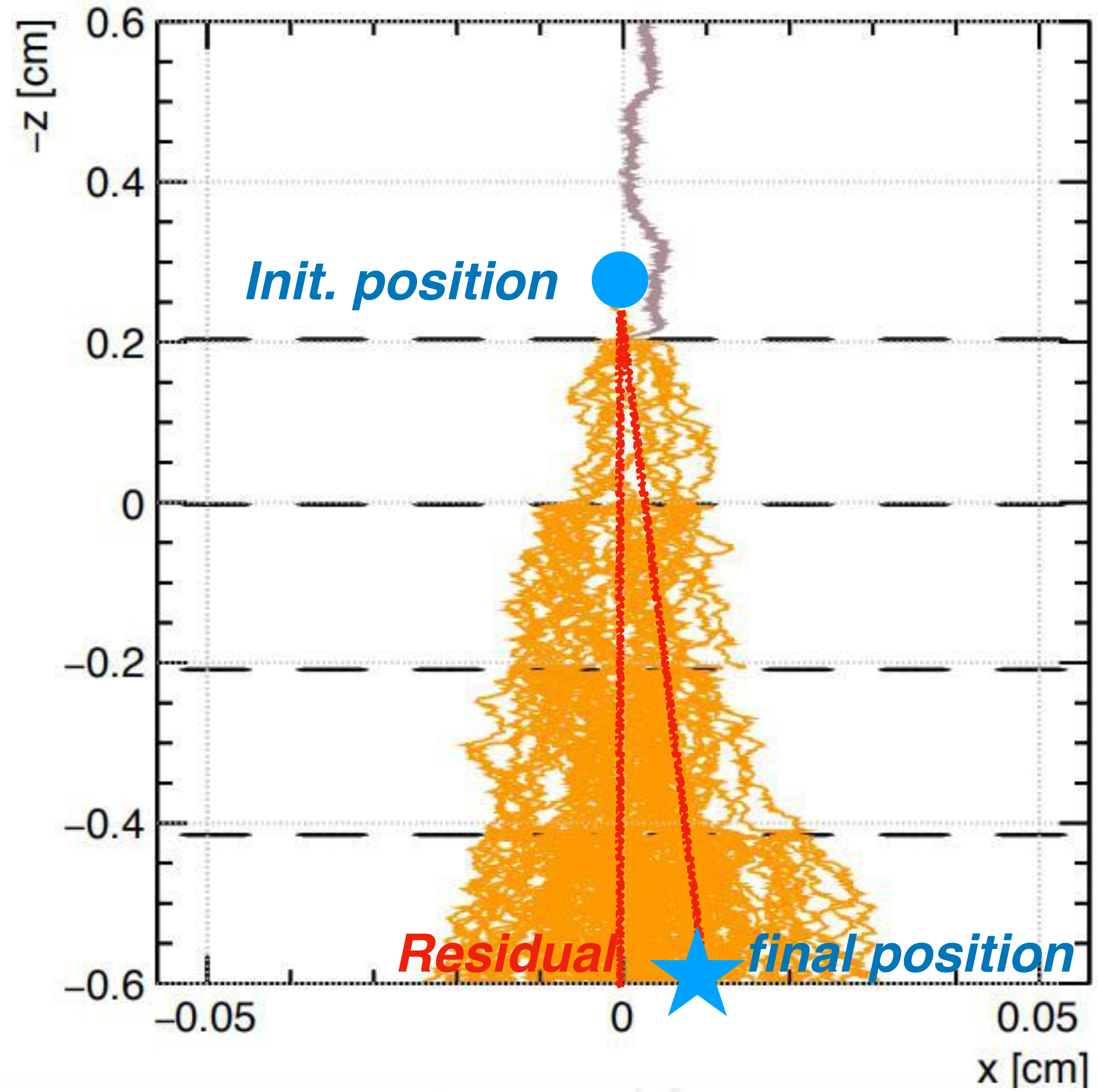
Spatial Resolution



Single HV



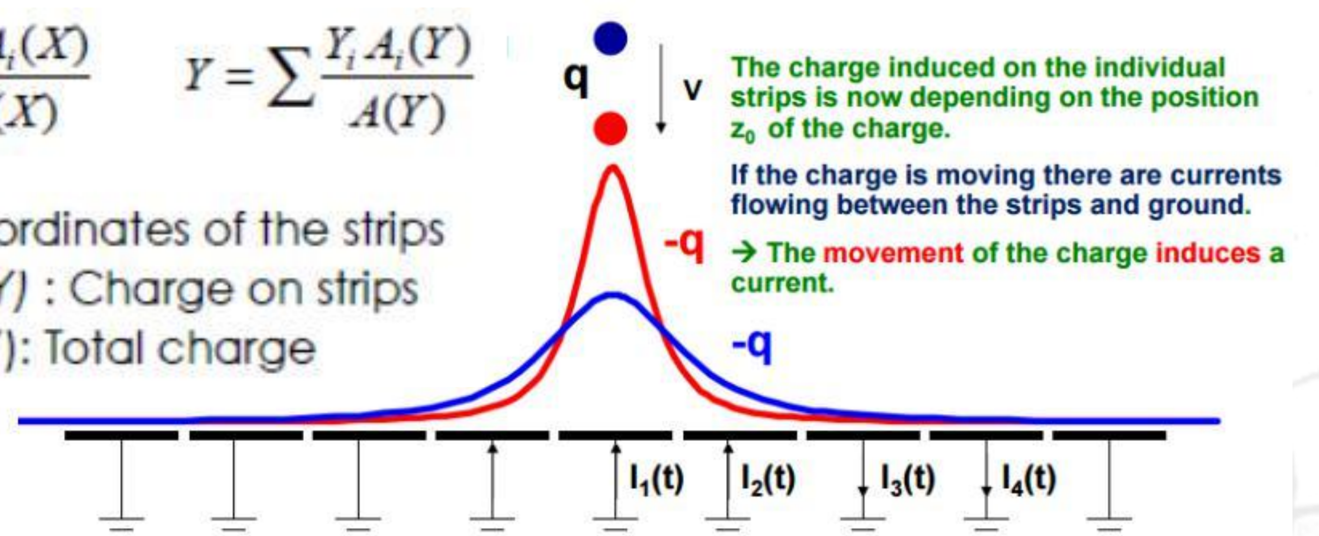
Double HV



center of gravity method

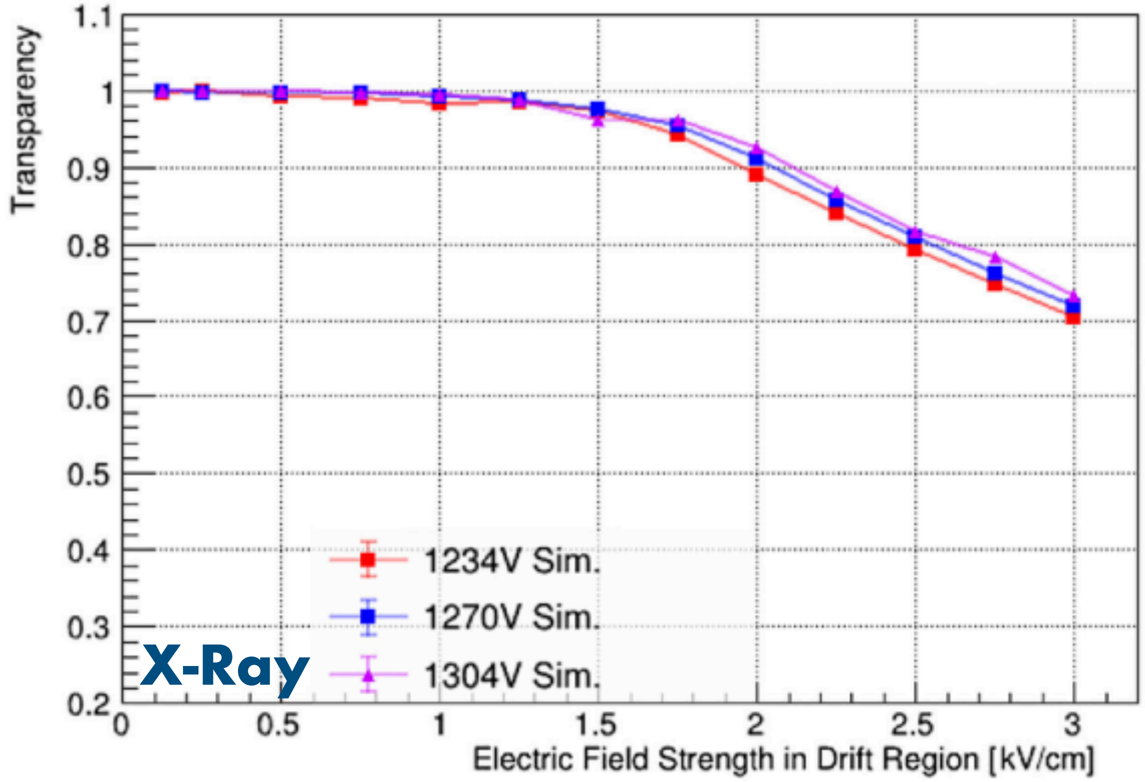
$$X = \sum \frac{X_i A_i(X)}{A(X)} \qquad Y = \sum \frac{Y_i A_i(Y)}{A(Y)}$$

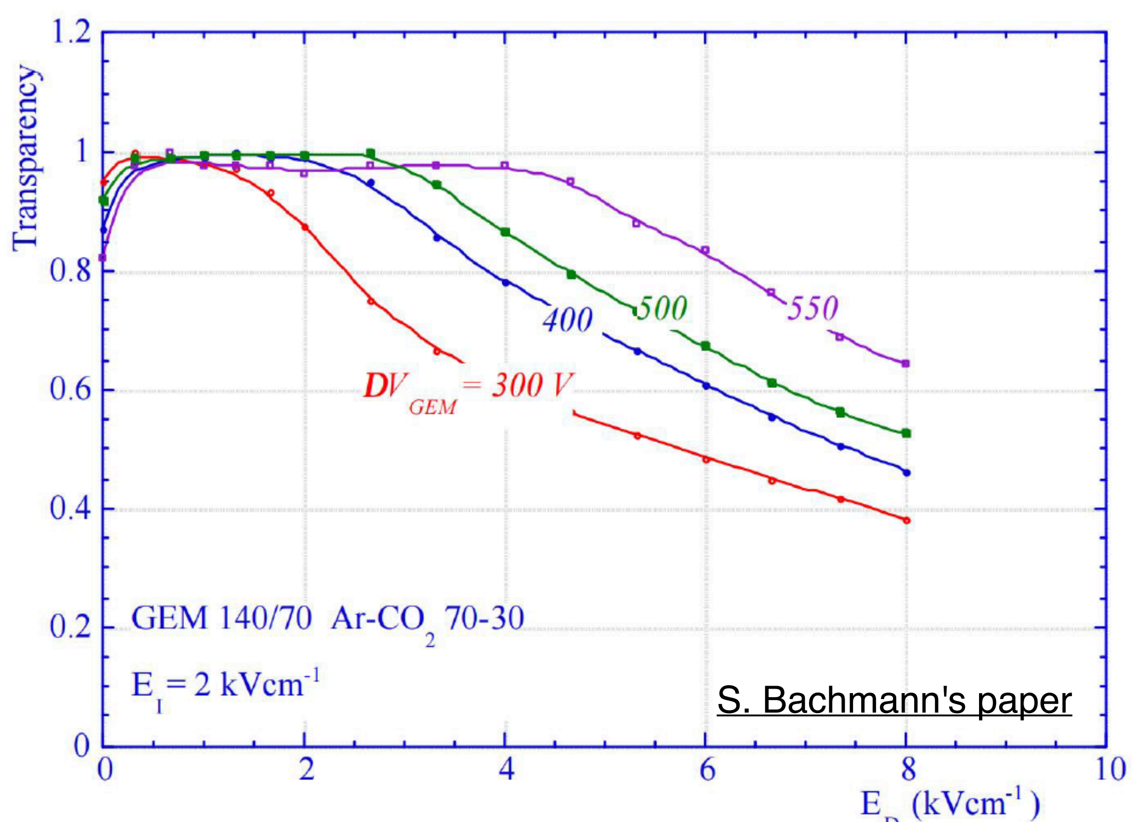
X_i, Y_i: Coordinates of the strips
$A_i(X)$, $A_i(Y)$: Charge on strips
A(X), A(Y): Total charge

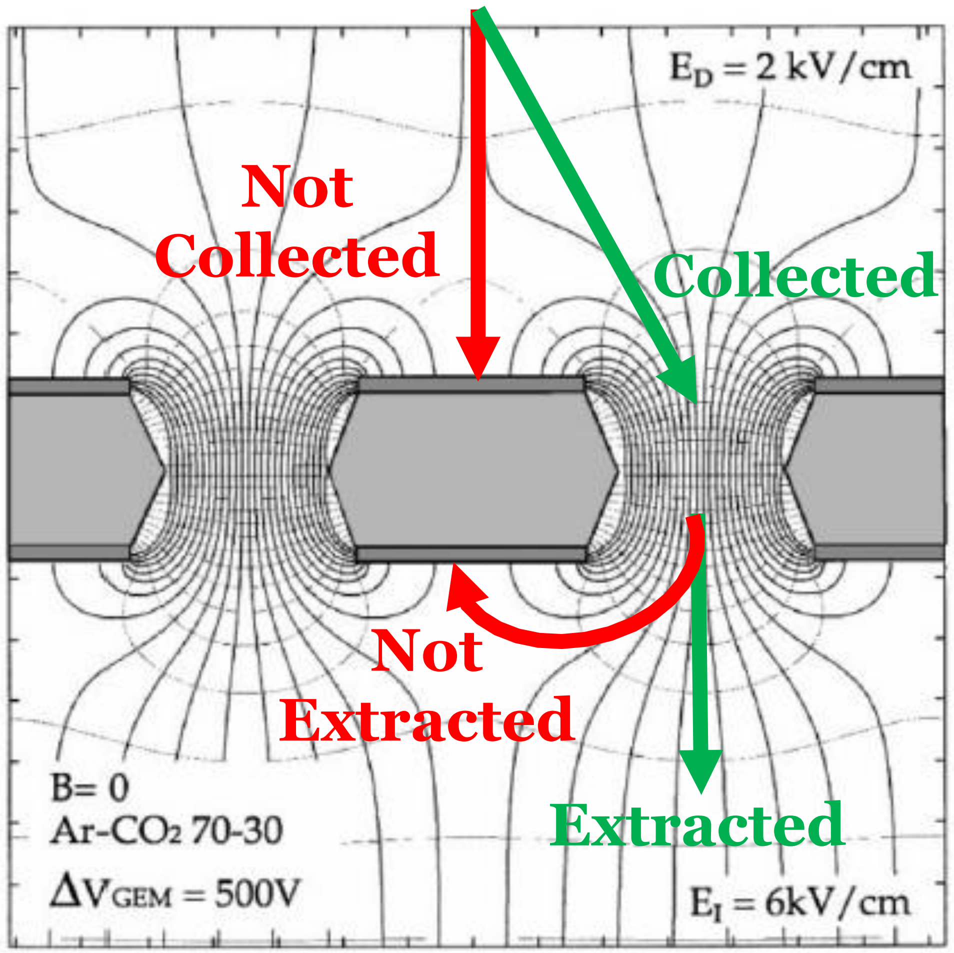


Transparency (Collection efficiency)

Simulation of Quadruple GEM

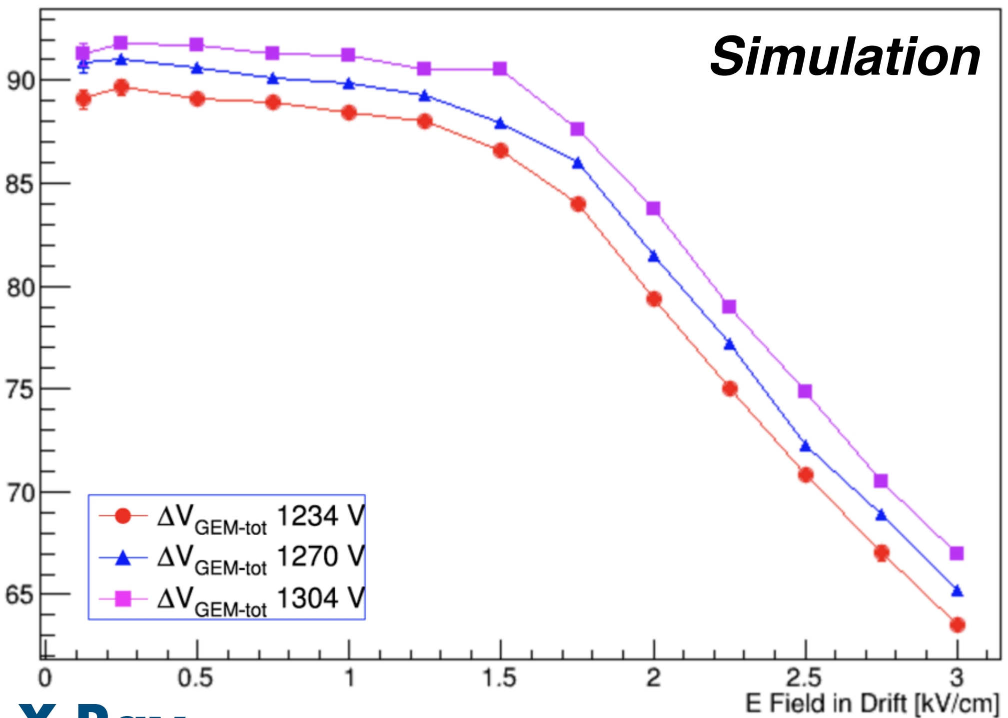






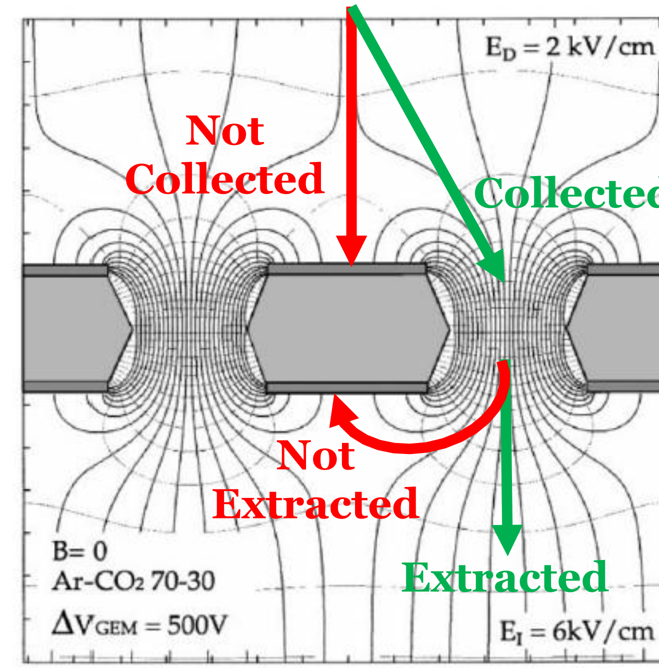
- Consistent with the experiment data.

Transparency(Collection efficiency)



X-Ray

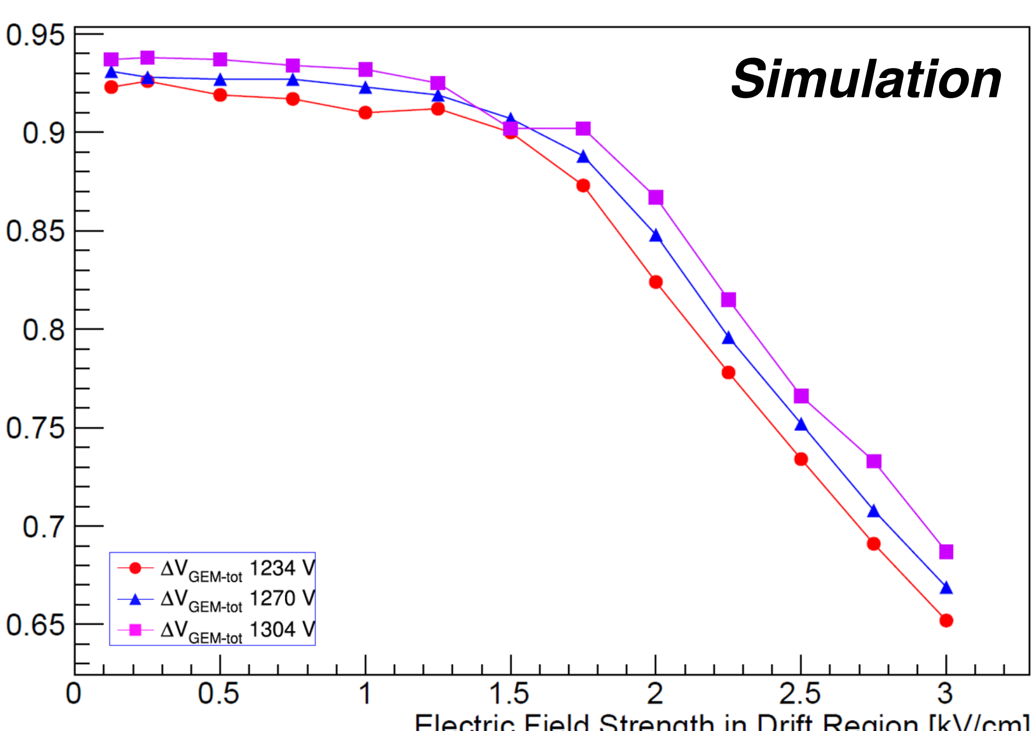
$$\text{transparency} = \epsilon_{\text{coll.}} \times \epsilon_{\text{extr.}}$$



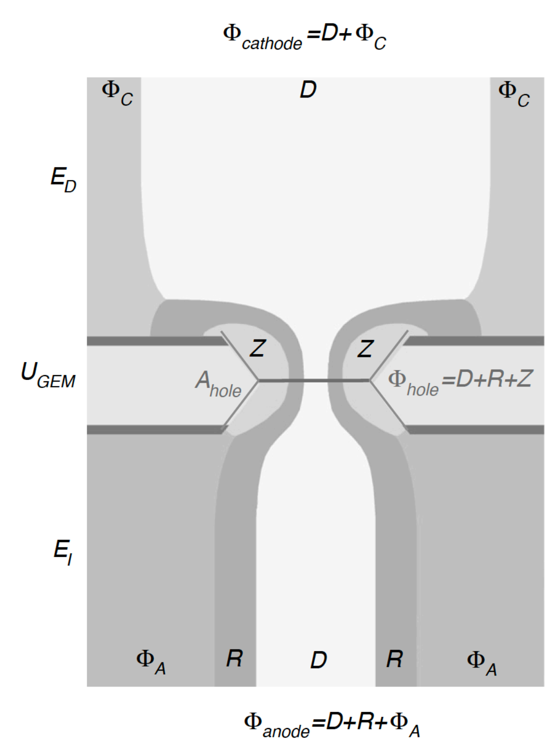
$\varepsilon_{coll,GEM1} \times Gain_{GEM1} \times \varepsilon_{extr,GEM1}$ × $\varepsilon_{coll,GEM2} \times Gain_{GEM2} \times \varepsilon_{extr,GEM2}$ × $\varepsilon_{coll,GEMN} \times Gain_{GEMN} \times \varepsilon_{extr,GEMN}$

= Effective Gain!!!

Collection Efficiency

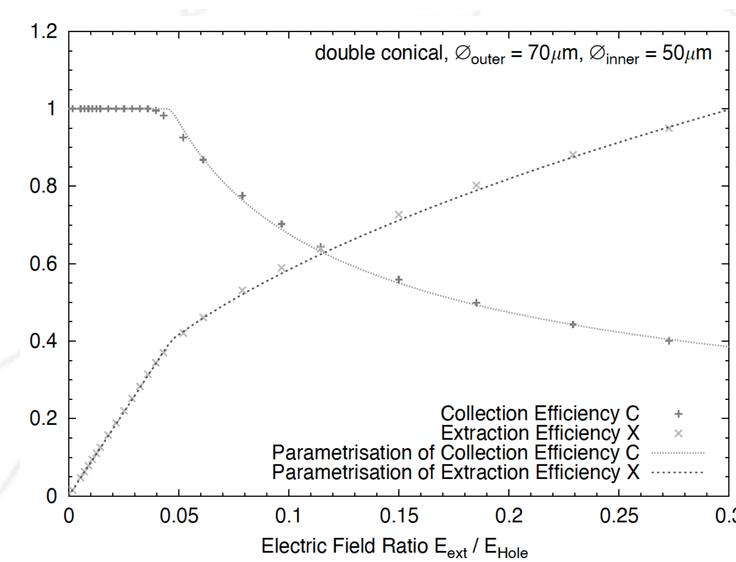


150GeV muon



$$C = \begin{cases} 1 & \text{for } E_{ext}/E_{hole} \leqslant r^{1/s} \\ r(E_{ext}/E_{hole})^{-s} & \text{for } E_{ext}/E_{hole} > r^{1/s}. \end{cases} \quad (8)$$

$$X = \begin{cases} \frac{1}{T_{opt}}(E_{ext}/E_{hole}) & \text{for } E_{ext}/E_{hole} \leqslant r^{1/s} \\ \frac{r}{T_{opt}}(E_{ext}/E_{hole})^{1-s} & \text{for } E_{ext}/E_{hole} > r^{1/s}. \end{cases} \quad (9)$$



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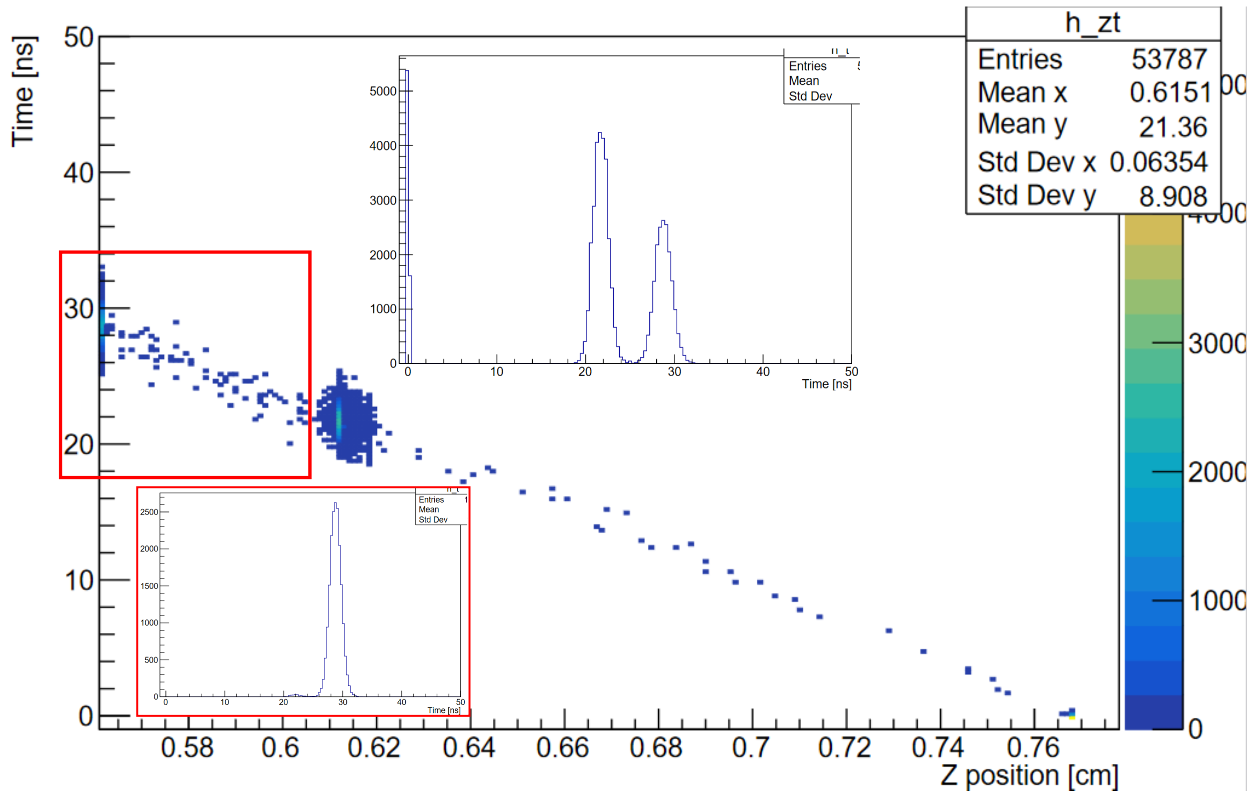
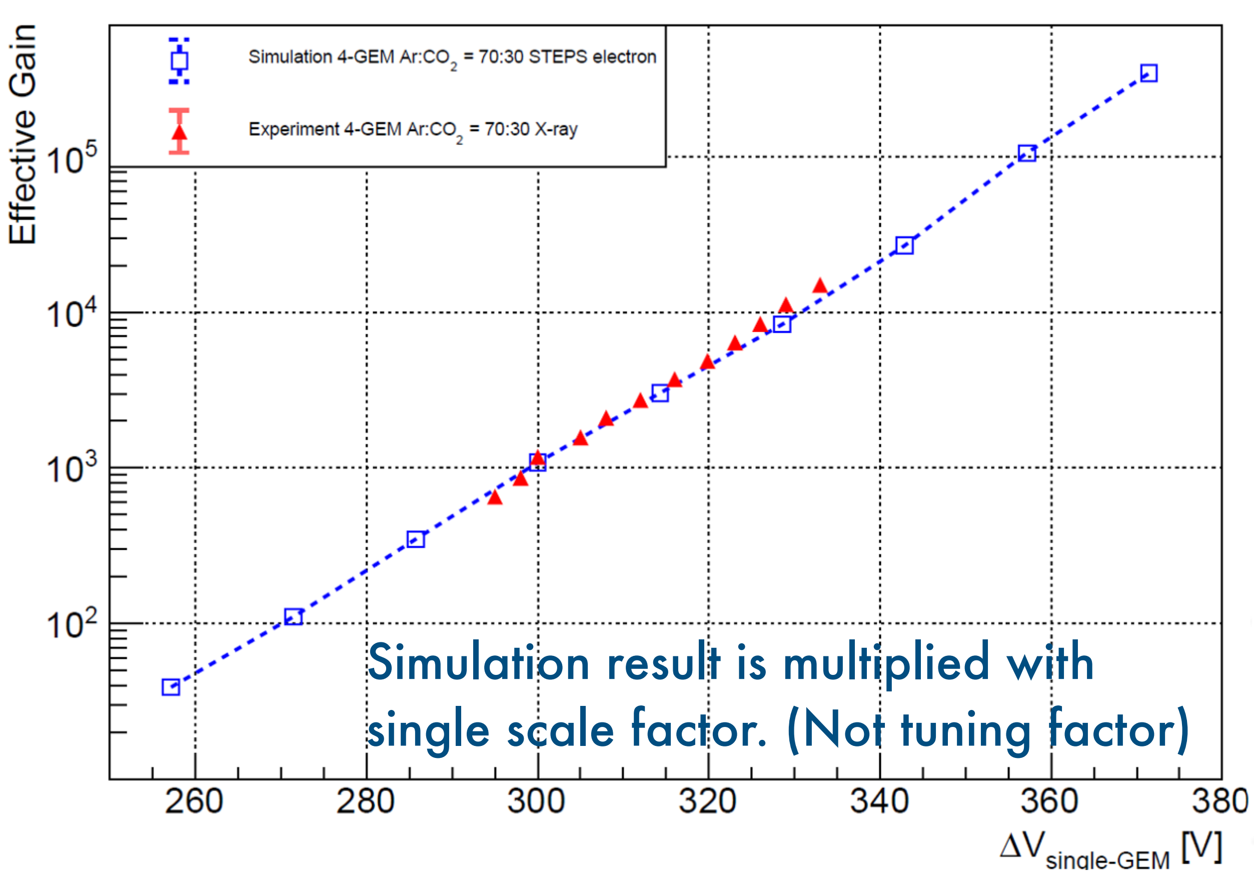
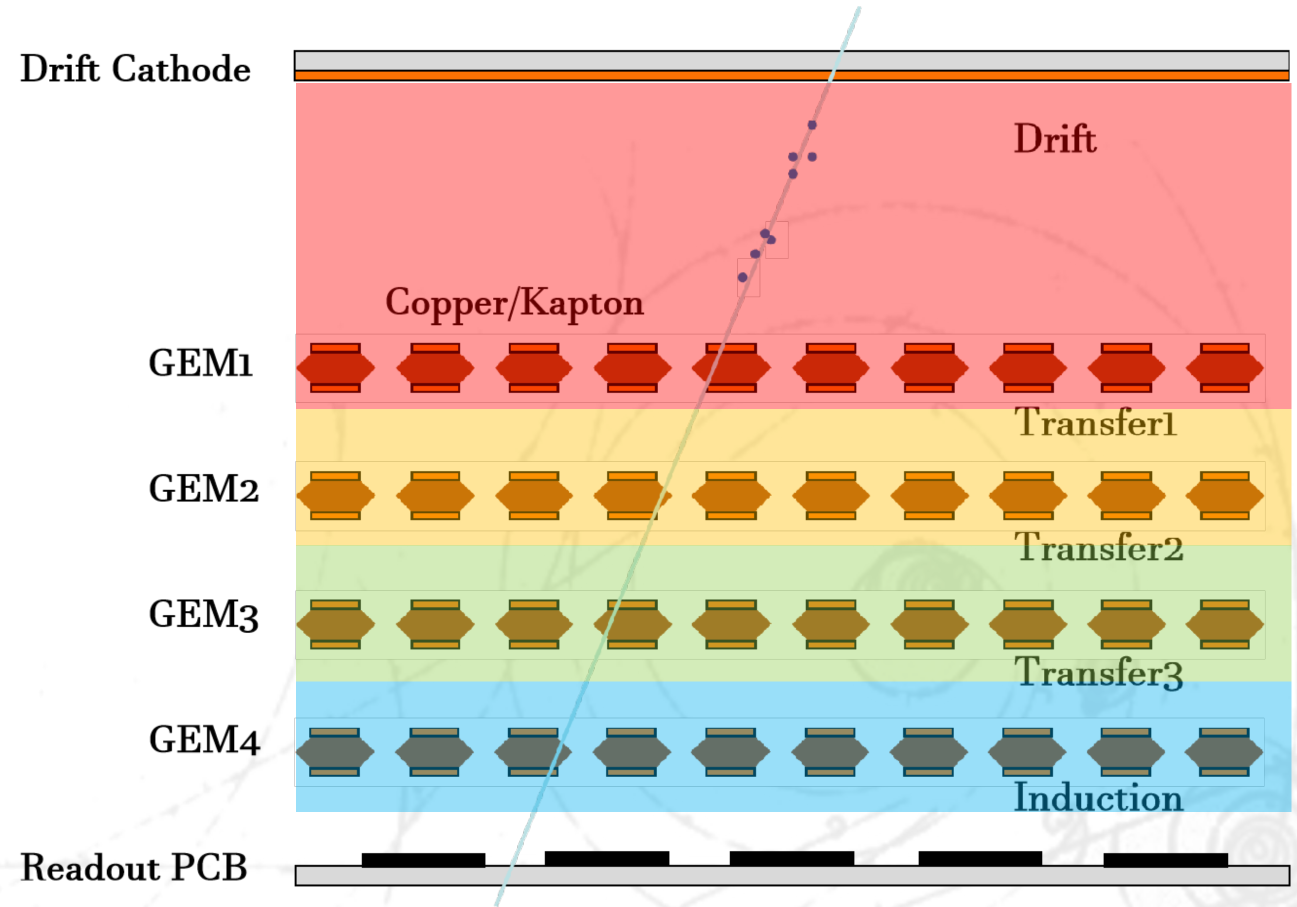
Results STEPS simulation



- Different regions can also be studied separately.
- Not only increase the simulation speed, but also helps to study the mechanism further.
- Left figure shows the electron end points on t-z plot
- A preliminary effective gain results can be seen in the left-button panel, the slope is quite similar with the experiment.

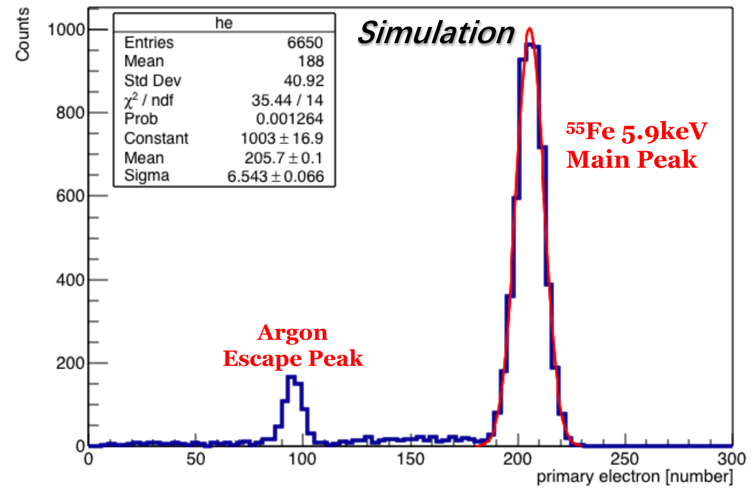




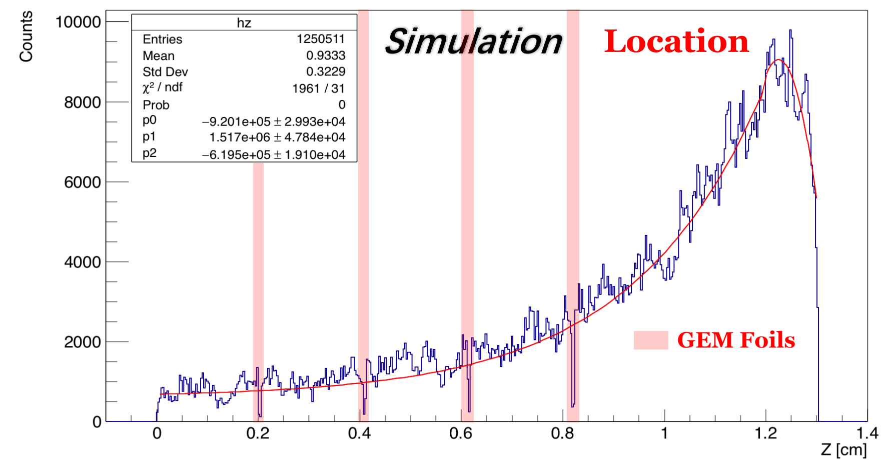
Backup

Insert Particle **Ionization**

Where are the primary electrons located and how many are there?



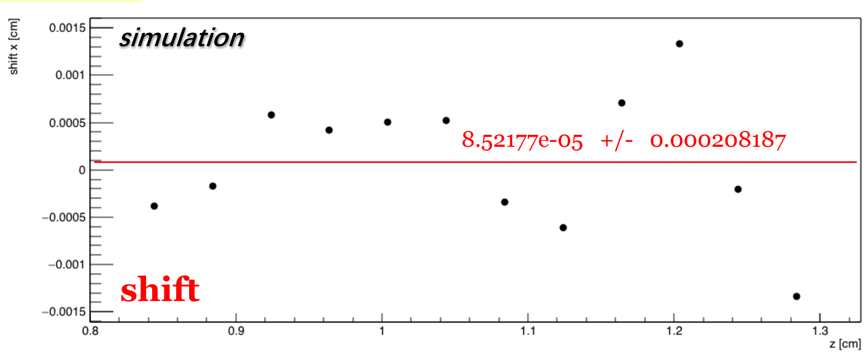
- Primary electron number (generated by single photon) distribution of simulated ^{55}Fe source.

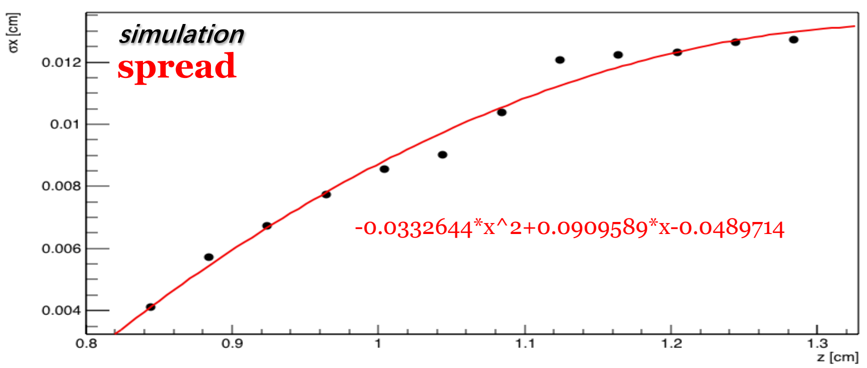


- Distribution of primary electron generation position. Fitting with exponential and parabola curves.

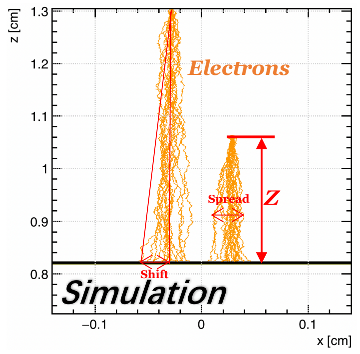
Drift

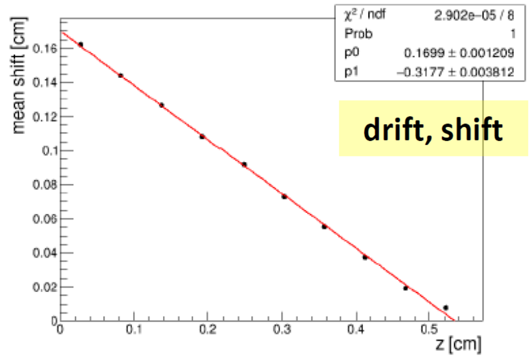
How particles go through the gaps and holes full of gas medium?

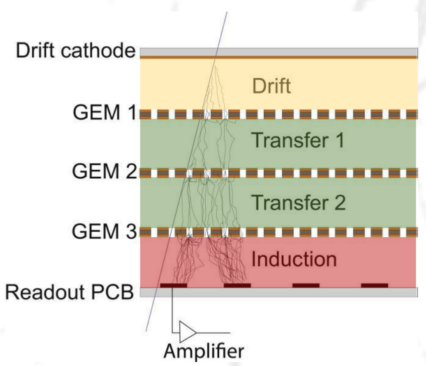




- Position(Z direction) dependence of shift and spread(sigma of shift, diffusion of electron end points) of free electrons moving in electric-magnetic fields(No magnetic fields applied in this situation, so shift is almost zero).





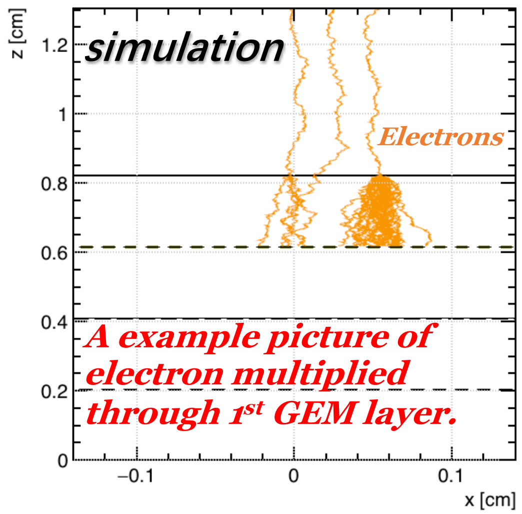


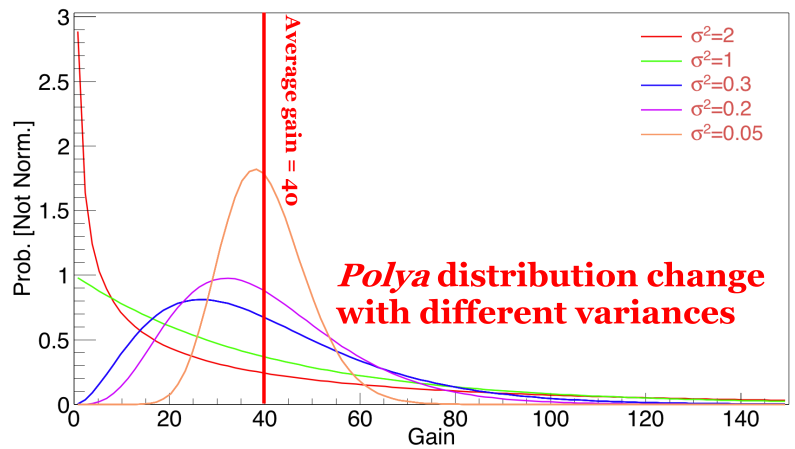
* from CMS-TDR-013

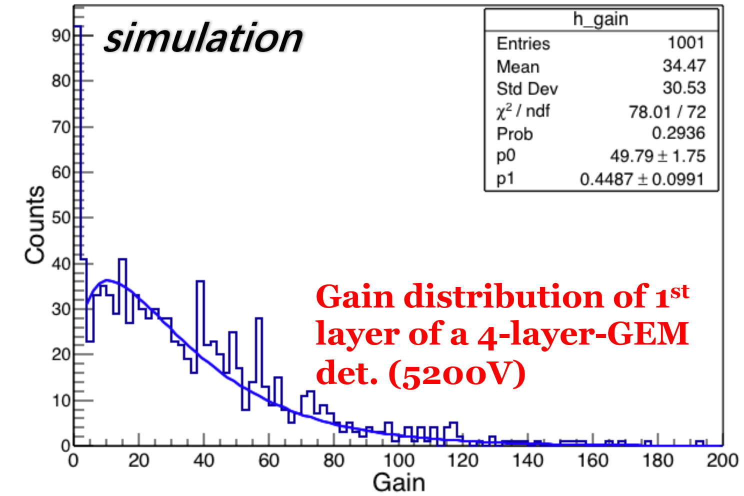
Backup

Multiplication

Gain of the foils means how many avalanche(daughter) electrons are generated by one single primary(mother) electron.



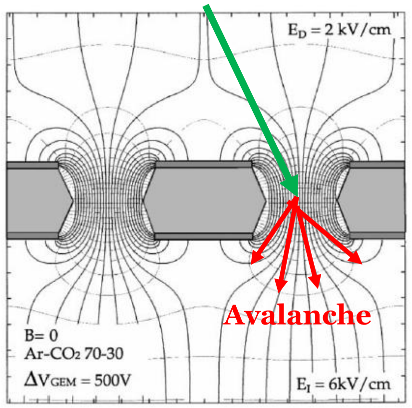




- The fluctuations of gain can be described pretty well by the ***Polya distribution***[2], but it lacks any physical interpretation.

$$P(G) = C_0 \frac{(1+\theta)^{1+\theta}}{\Gamma(1+\theta)} \left(\frac{G}{\bar{G}}\right)^{\theta} \exp\left[-(1+\theta)\frac{G}{\bar{G}}\right]$$

- Where $\bar{G}$ is the average gain and θ is the parameter related to relative gain variance $\sigma^2 = 1/(1+\theta)$.



$\varepsilon_{coll,GEM1} \times Gain_{GEM1} \times \varepsilon_{extr,GEM1}$ × $\varepsilon_{coll,GEM2} \times Gain_{GEM2} \times \varepsilon_{extr,GEM2}$ × $\varepsilon_{coll,GEMN} \times Gain_{GEMN} \times \varepsilon_{extr,GEMN}$ = Effective Gain!!!